PITZ1: Optimizing an Electron Source for FELs

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for PITZ Team

The **P**hoto **I**njector **T**est Facility at DESY **Z**euthen (**PITZ**) was built to test and optimize electron sources for Free Electron Lasers and future colliders. The focus is on the production of intense electron beams with minimum transverse emittance and short bunch length as required for FEL operation.

Physics aspects of the first phase of the test facility (PITZ1) will be discussed. Recent results on electron source characterization will be presented. This will include measurements of the transverse and longitudinal phase space as a function of different parameters.

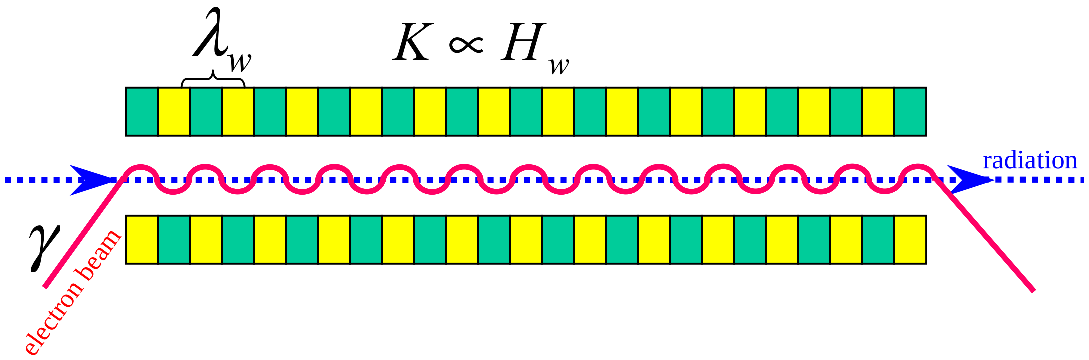
As a first application of the PITZ electron source the installation of the PITZ1 injector at the TESLA Test Facility Free Electron Laser at DESY Hamburg is ongoing right now.

Outline

	keywords
•Introduction and motivation	FEL, SASE, XFEL
•PITZ1 research program	
–RF Conditioning	long RF pulse, dark current
–Cathode laser properties	Gaussian, flat-top profile
–Electron beam measurements	beam charge, longitudinal momentum, bunch length, normalized emittance
•Conclusions	
•PITZ2 overview	emittance conservation booster cavity

Introduction: FEL

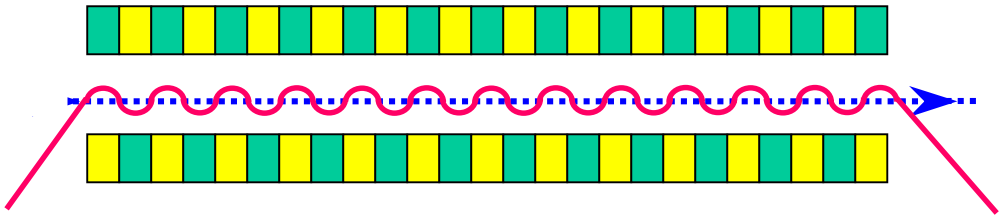
In a free-electron laser (FEL), the magnetic field of the undulator magnet causes the electrons to oscillate transversely and at resonant wavelength λ_{ph}



$$\lambda_{ph} = \lambda_w \frac{1+K^2}{2\gamma^2}$$

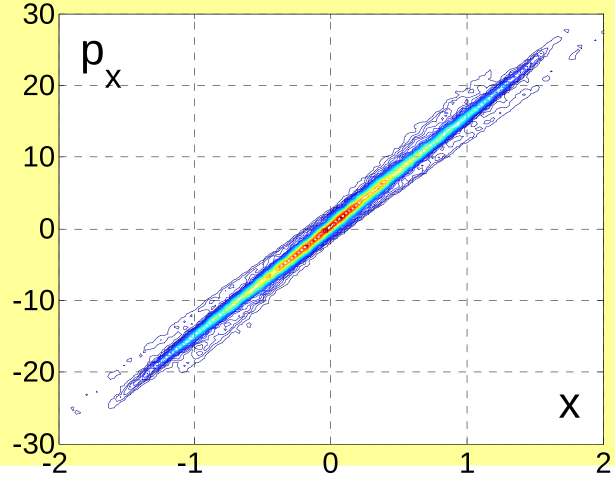
These oscillations induce micro-bunching on a scale of λ_{ph}, which causes electrons within the micro-bunch to radiate coherently at the resonant wavelength.

In the **oscillator** configuration, the laser light reflects back and forth between mirrors, gaining strength on each pass.

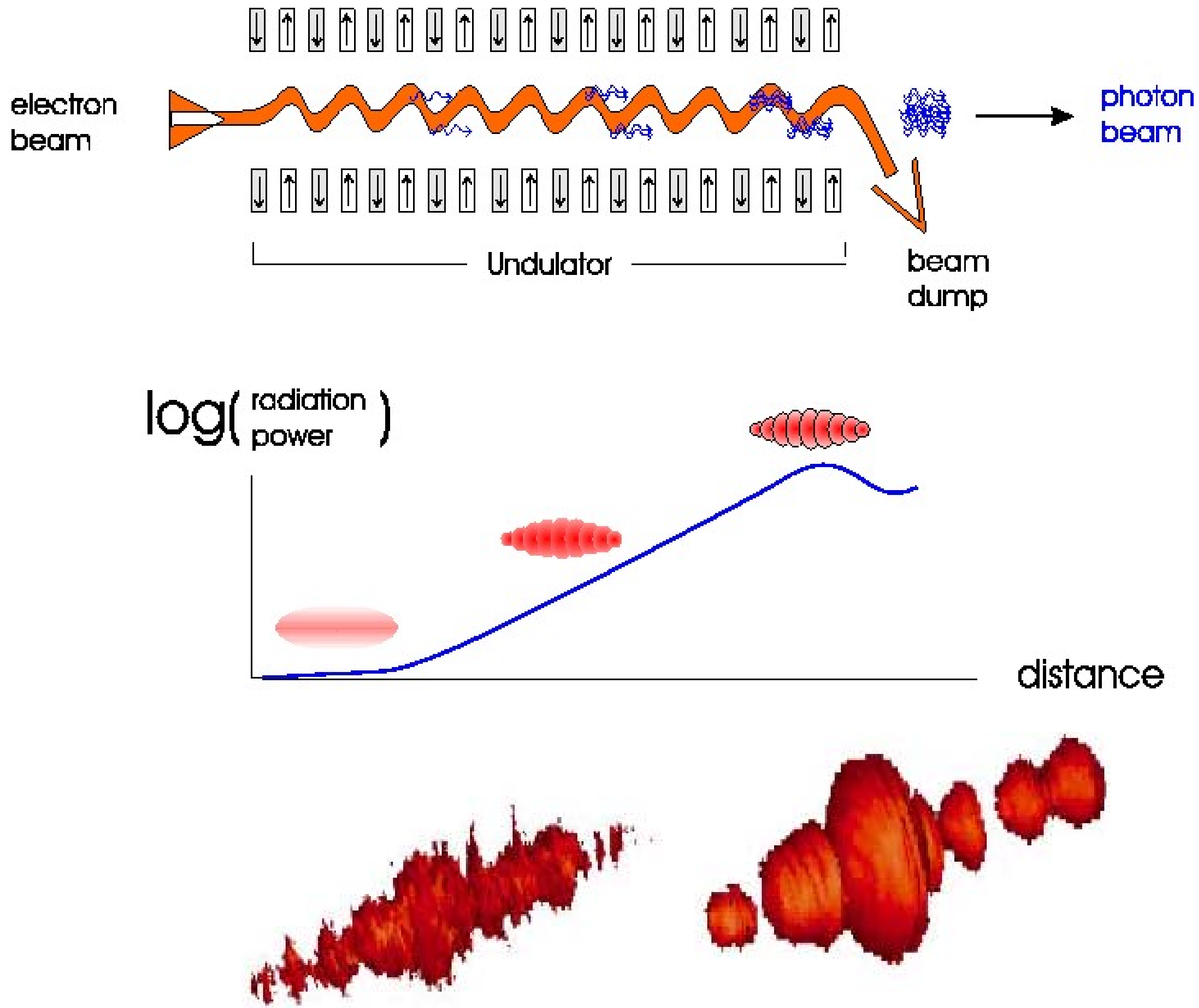


At ultra-short wavelength, less than 100 nm, mirrors are not available. In such a case, at high phase space density of an electron bunch the FEL instability develops in a single pass through the undulator, the process is referred to as **s**elf-**a**mplified **s**timulated **e**mission (**SASE**).

Emittance ~ area of the phase space, i.e. (x, p_x)

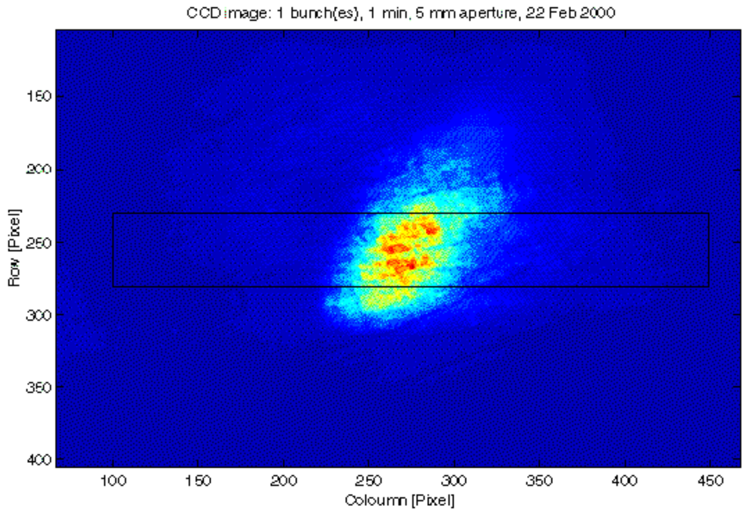


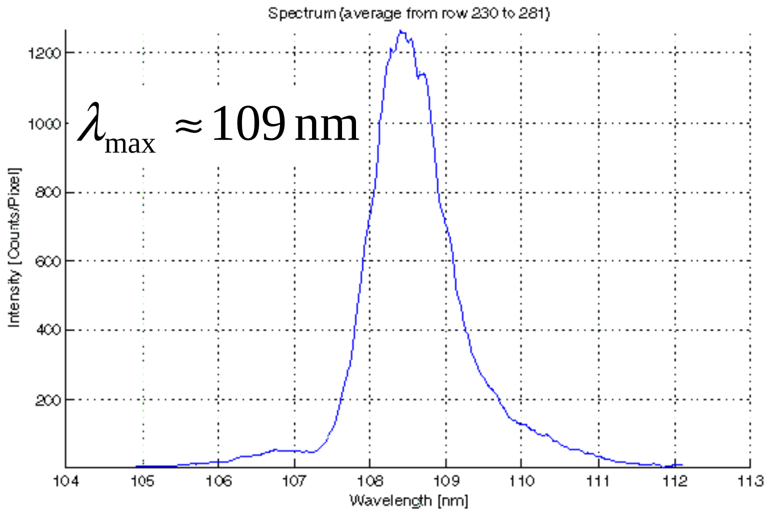
Introduction: SASE FEL Principles



TTF-FEL 1

First Lasing at the TESLA Test Facility
(22.02.2000, 4:47 a.m, E_{beam}=233MeV)





Summary of the main parameters achieved at TTF-FEL 1*

Electrons	
beam energy	200 - 270 MeV
bunch charge	2.7 - 3.3 nC
charge in lasing part of bunch	0.1 - 0.3 nC
duration of radiative part of bunch	50 - 150 fs
peak current	(1.3 ± 0.3) kA
rms normalized emittance	(6 ± 2) mm-mrad
Undulator	
undulator period λ_w	27.3 mm
undulator peak field	0.47 T
average beta-function	1.2 m
magnetic length of undulator	13.5 m
Photons	
radiation wavelength	80 - 120 nm
energy in the radiation pulse	30 - 100 μJ
FWHM radiation pulse duration	50 - 200 fs
radiation peak power lewel	1 GW
spectral width (FWHM)	1%
rad. spot size at undulator exit (FWHM)	250 μm
radiation angular divergence (FWHM)	260 μrad

* TESLA FEL Reports 2002-08

Toward to TTF-FEL 2 and TESLA XFEL

TTF-FEL 1 has demonstrated the feasibility of radiation source in the **VUV** regime using the **SASE** principle.

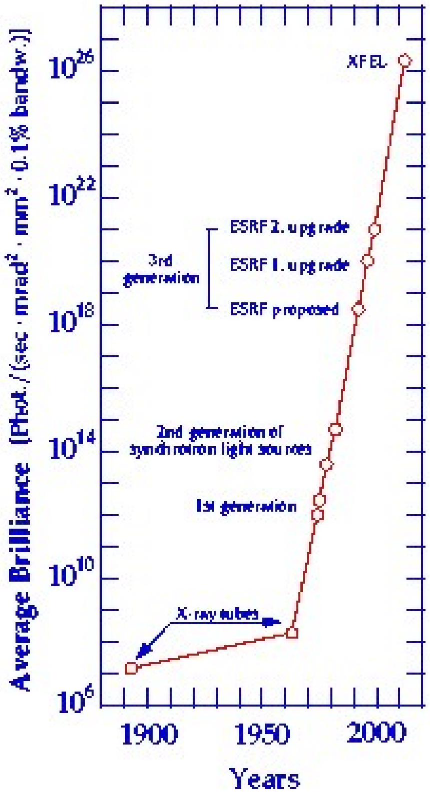
TTF-FEL 2

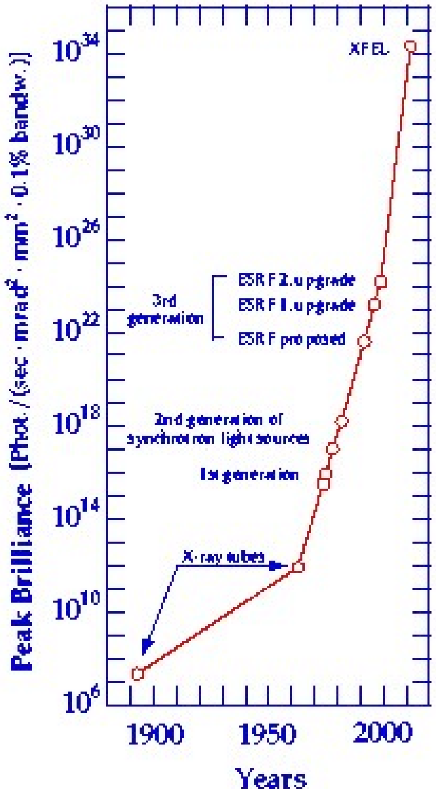
- wavelength $\lambda \downarrow$ **6 nm**
- beam energy $E_{beam} \uparrow$ **1 GeV**

required:

- normalized transverse emittance ε **< 2 π-mm-mrad**
- peak current I_{peak} **> 2.5 kA**.

TESLA-XFEL





- $\lambda \sim$ **1Å**
- $E_{beam} \sim$ **20 GeV**

required:

$\varepsilon \sim$ **1.4 π-mm-mrad**

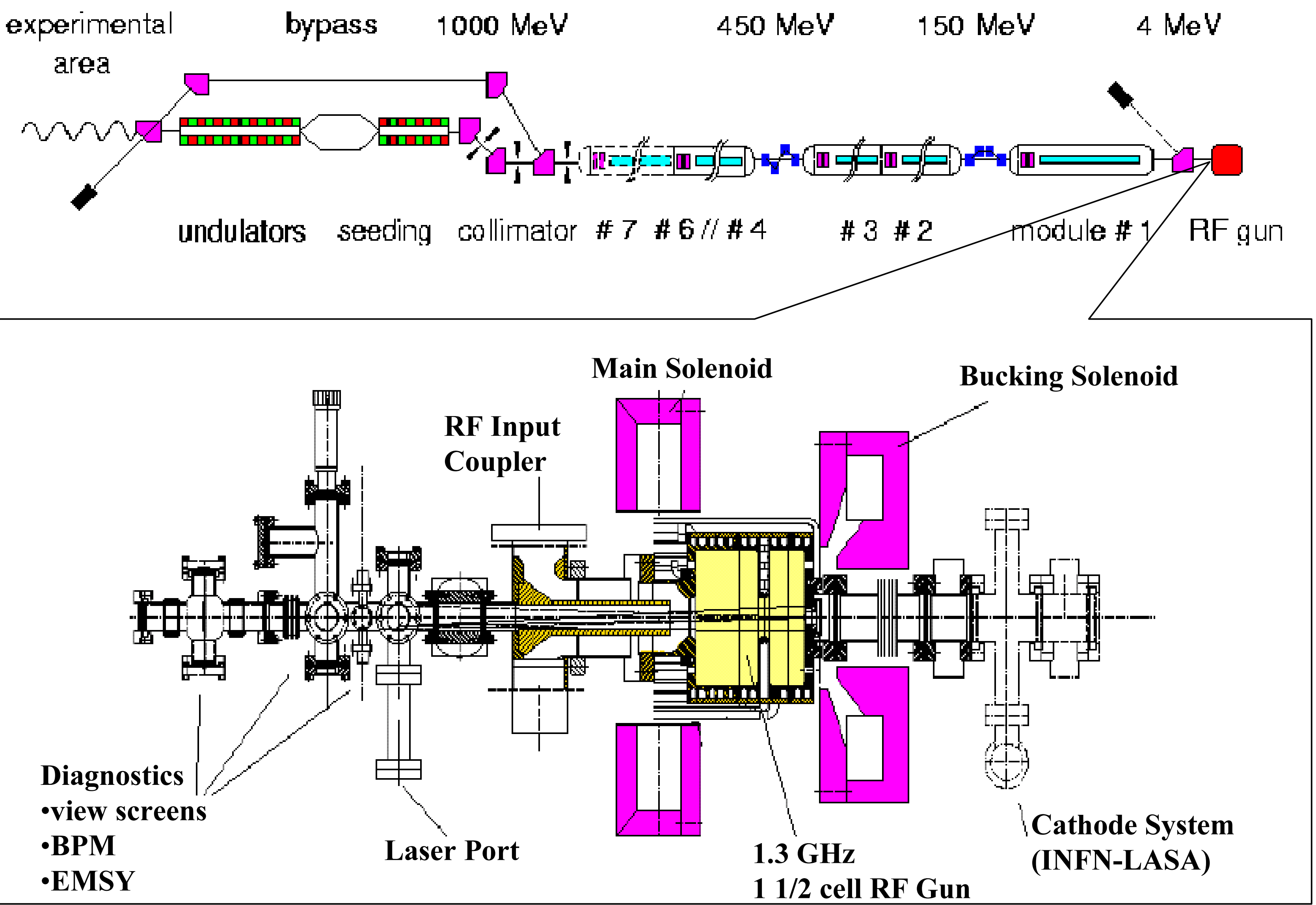
$I_{peak} \sim$ **5 kA**

Scientific Applications of XFEL Radiation

- **Atomic, Molecular and Cluster Phenomena**
- **Plasma Physics**
- **Condensed Matter Physics**
- **Surface and Interface Studies**
- **Materials Science**
- **Chemistry**
- **Life Sciences**
- **Nonlinear Processes and Quantum Optics**

High Brightness Photo-Injector for FEL

Beam quality in linac can only degrade → demands on the injector performance are very challenging.



RF-Gun (TTF 1)

$$E_z^{RF} = E(z) \cdot \sin(\omega t + \phi_0);\ \phi_0 \text{ - RF phase}$$

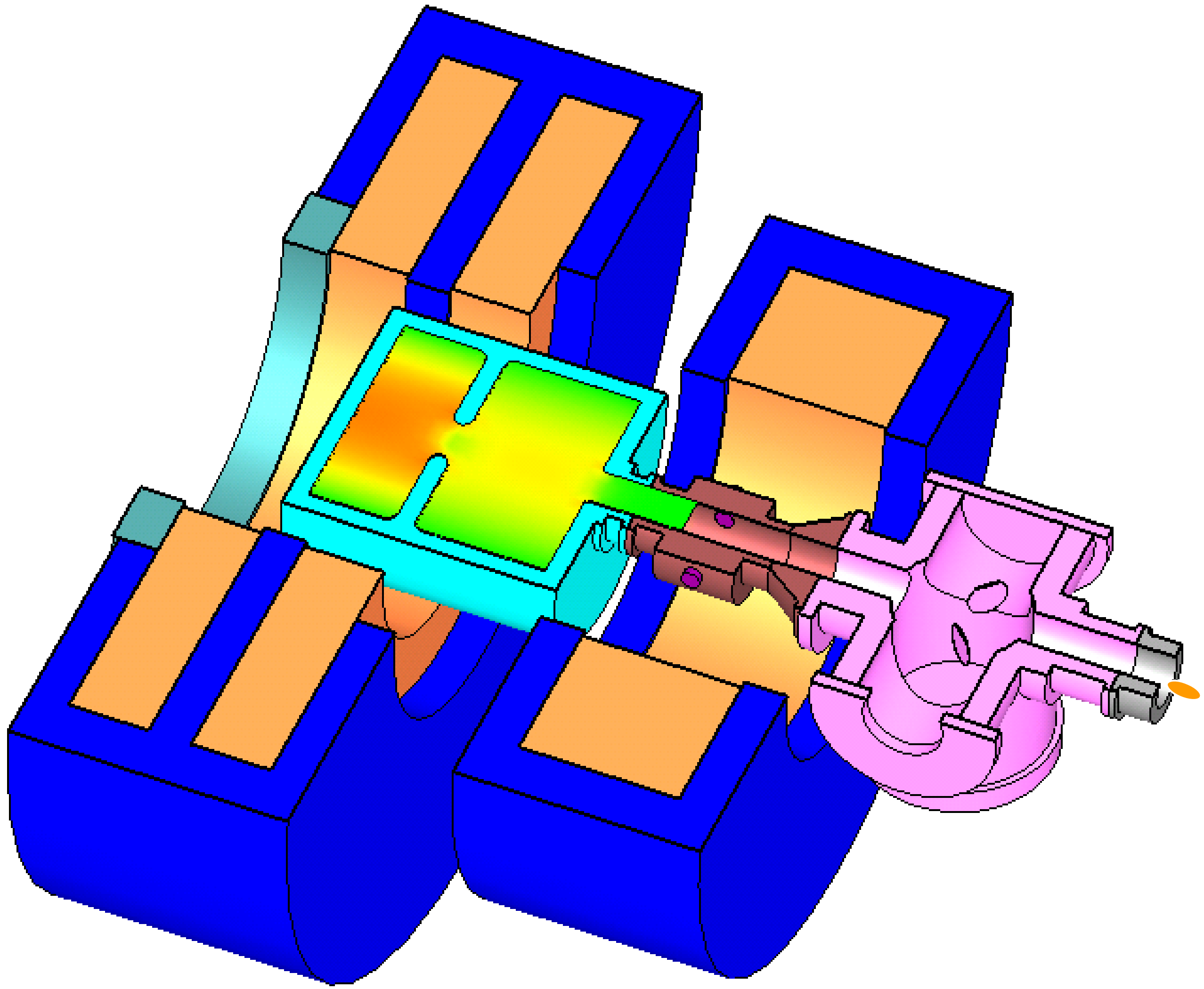
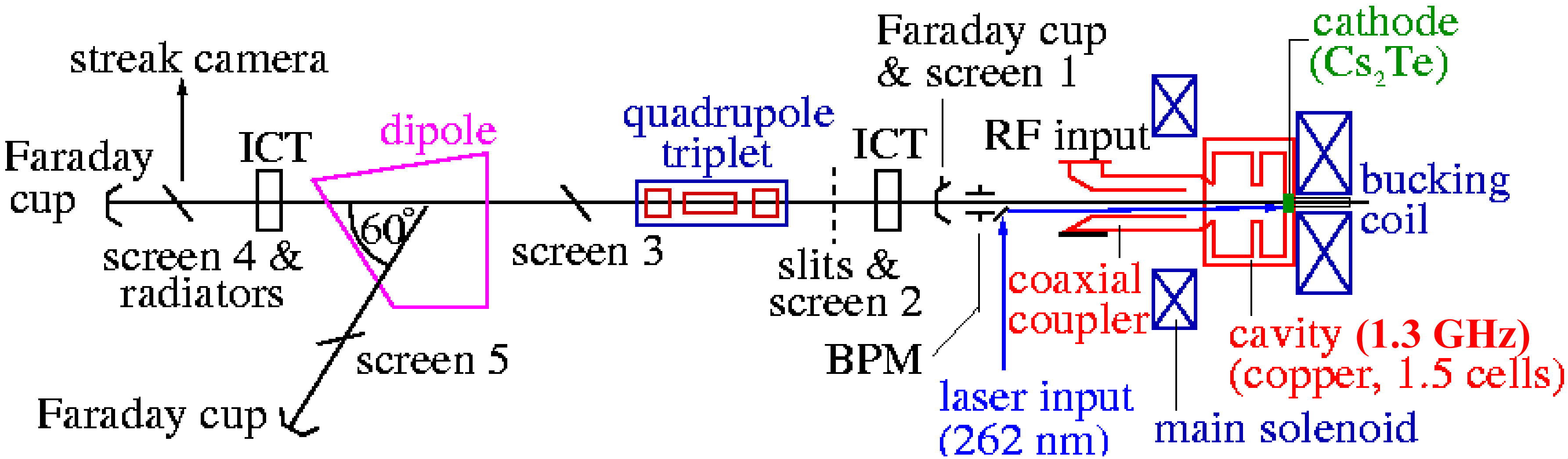


Photo-Injector Test Facility at DESY Zeuthen (PITZ)

Collaboration:

BESSY Berlin, DESY (HH + Z),
INFN Frascati, INFN Milano,
INR Troitsk, INRNE Sofia,
LAL Orsay, MBI Berlin,
TU Darmstadt, TU Eindhoven,
YERPHI Yerevan



PITZ: Main Goals and Motivation

- Test facility for injectors for FELs: focus on TTF2-FEL, XFEL

  ⇒ **very small transverse emittance (1π mm mrad @ 1 nC)**

  ⇒ stable production of short bunches with small energy spread

- Extensive R&D on photo injectors in parallel to TTF operation

- Compare detailed experimental results with simulations:

  ⇒ benchmark theoretical understanding of photo injectors

- Test and optimize RF guns for subsequent operation at TTF2-FEL and XFEL

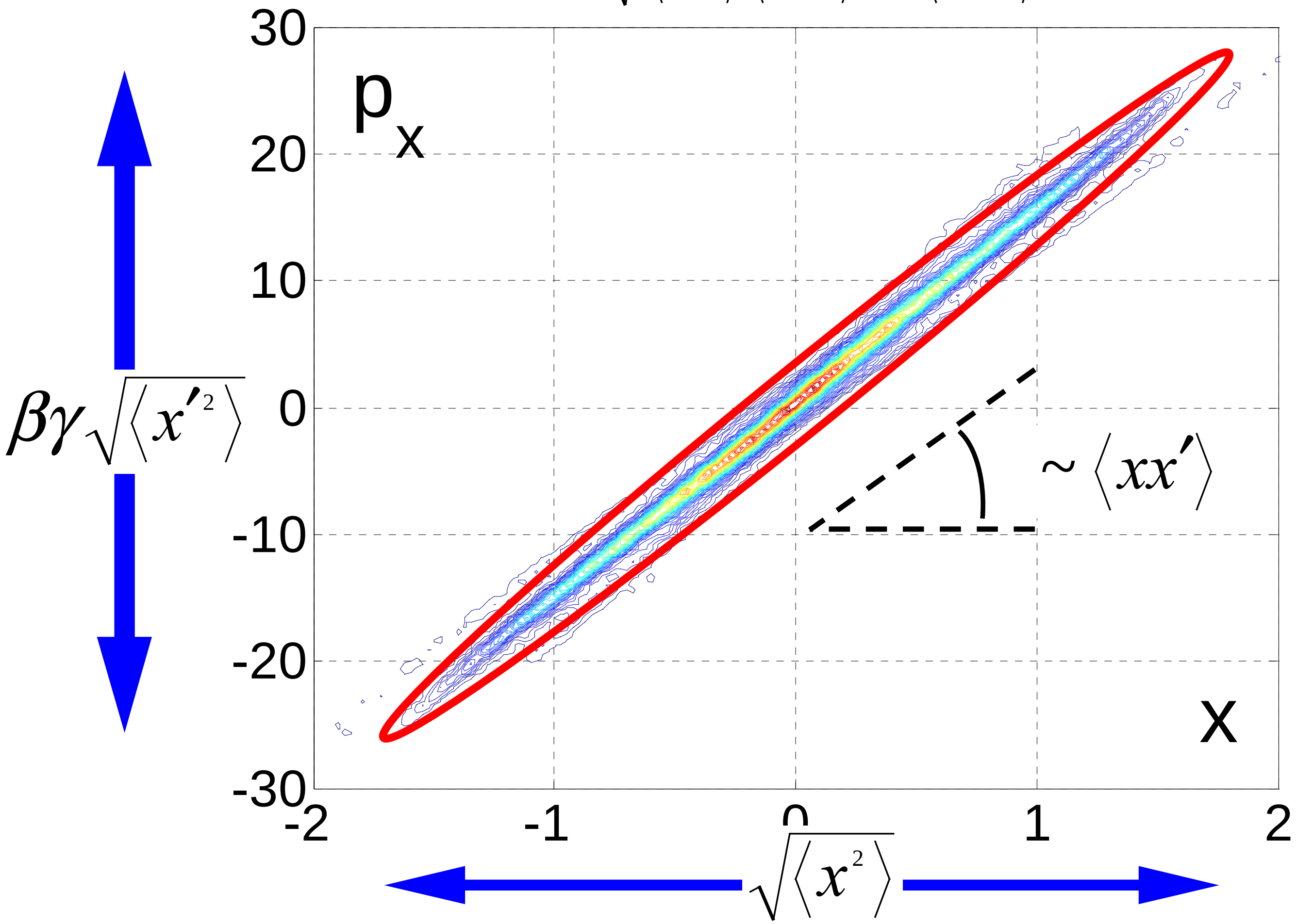
- Test new developments (laser, cathodes, beam diagnostics)

Transverse Beam Emittance

$$\text{PDF } f_6(x, p_x, y, p_y, z, p_z) \;\longrightarrow\; f_2(x, p_x \propto \beta\gamma x')$$

Normalized beam emittance

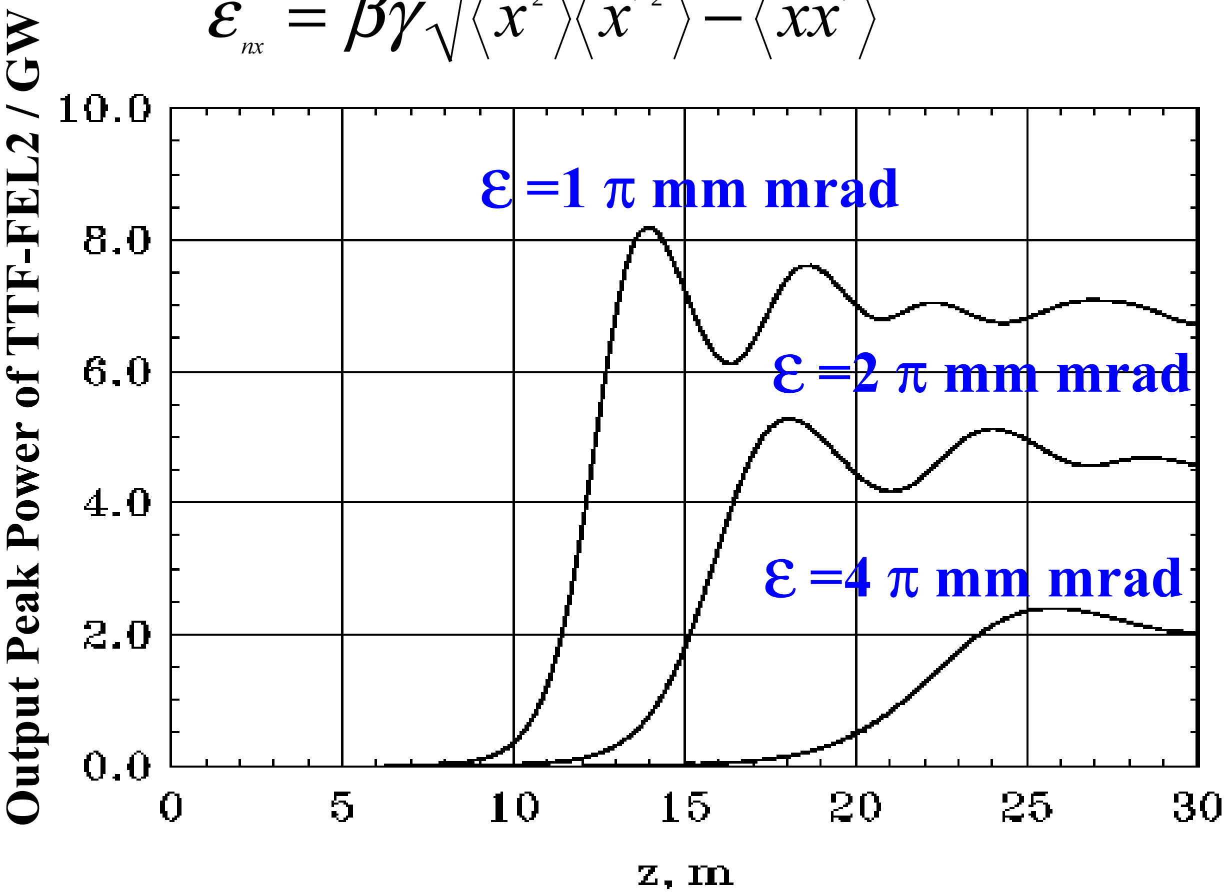
$$\varepsilon_{nx} = \beta\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

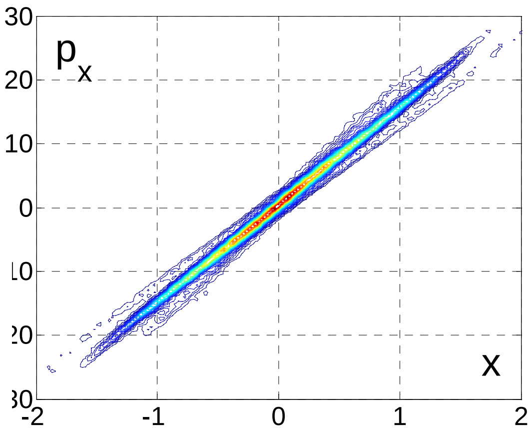


Beam Emittance Influence On FEL

Normalized beam emittance

$$\varepsilon_{nx} = \beta\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$





Smaller emittance:

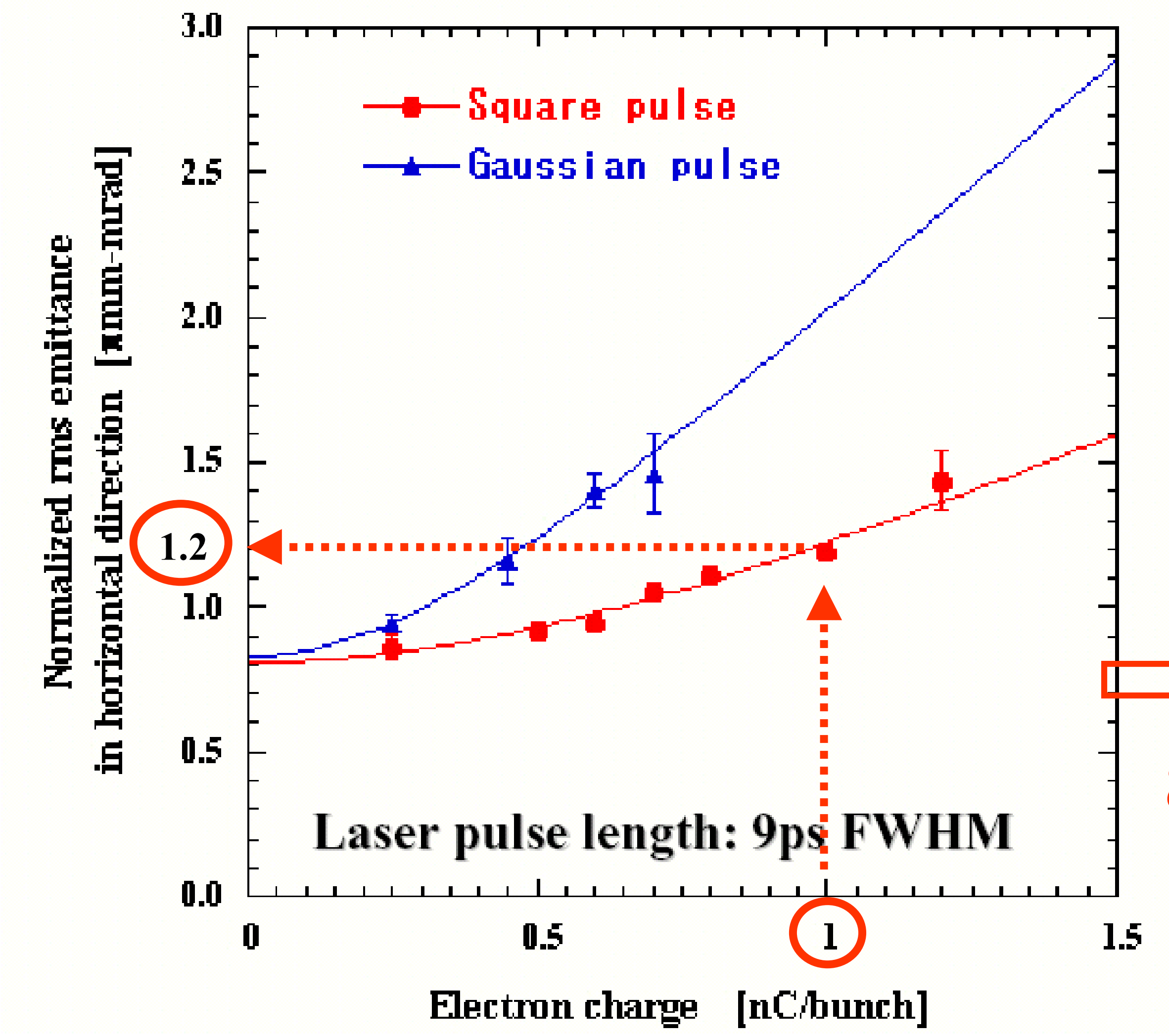
- Higher FEL gain → shorter undulator
- Higher radiation peak power

World Record on Emittance

Sumitomo Heavy Industries + FESTA, **Japan**

F. Sakai et. al., ICFA workshop 2002, SPring8

Emittance measurements for different laser pulse shapes

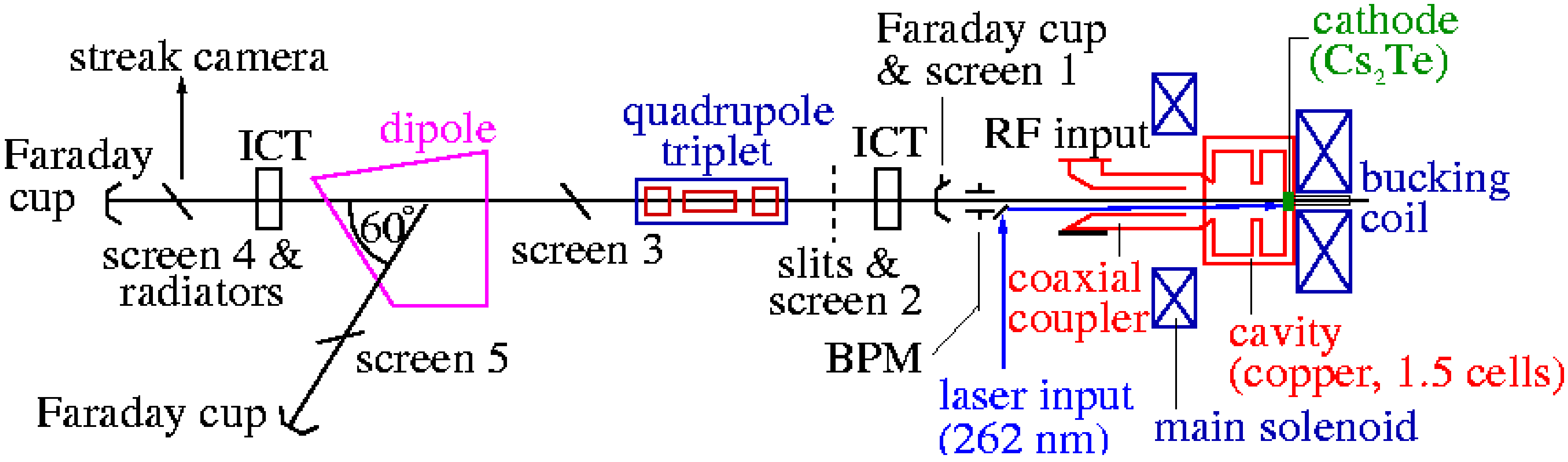


- S-band (2.856GHz)
- + Linac
- Quad scan technique
- Xemittance

For 1 nC:

$\varepsilon_n \approx 1.2\ \pi$ **mm mrad**

PITZ 1 Research Program

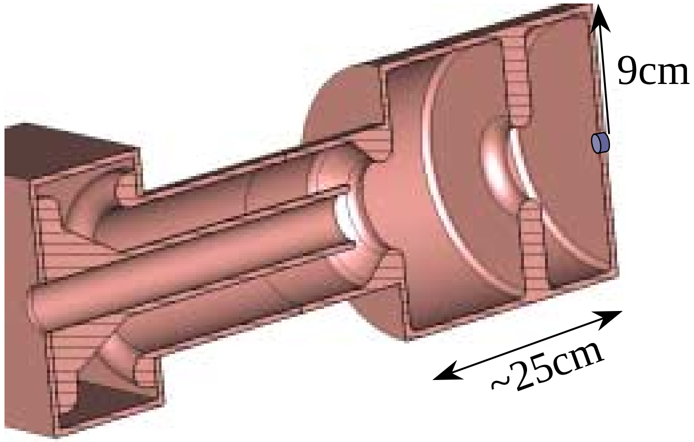


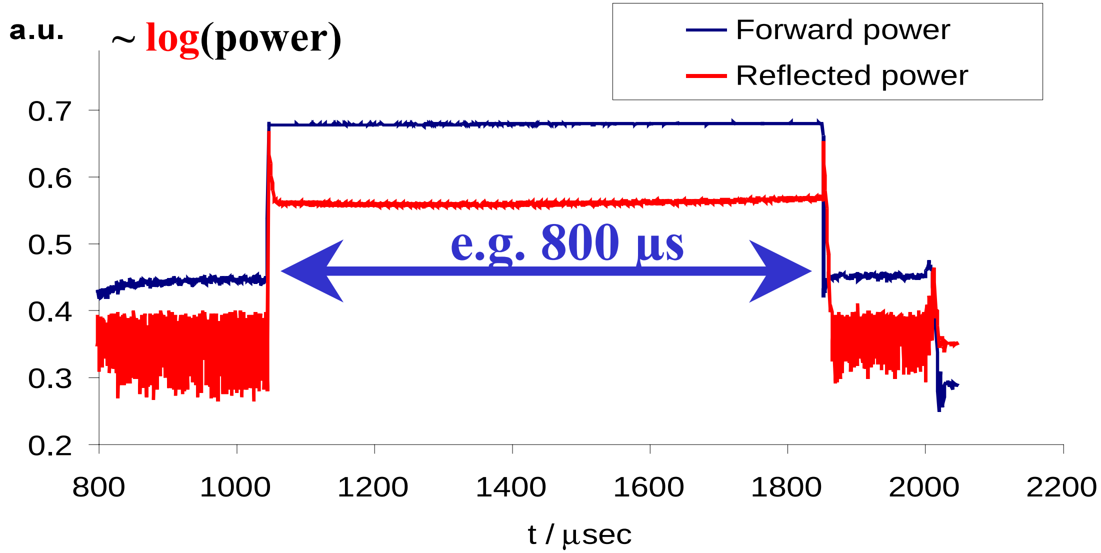
- Conditioning of the RF Gun
- Measurements of the laser beam properties
- Electron beam measurements:
  - ✓ charge
  - ✓ longitudinal momentum and momentum spread
  - ✓ bunch length
  - ✓ transverse size and normalized emittance

RF Gun Conditioning: Long Pulse High Power

RF Power source: 5 MW Klystron

RF Gun cavity: 1.5-cell copper cavity operated at 1.3 GHz





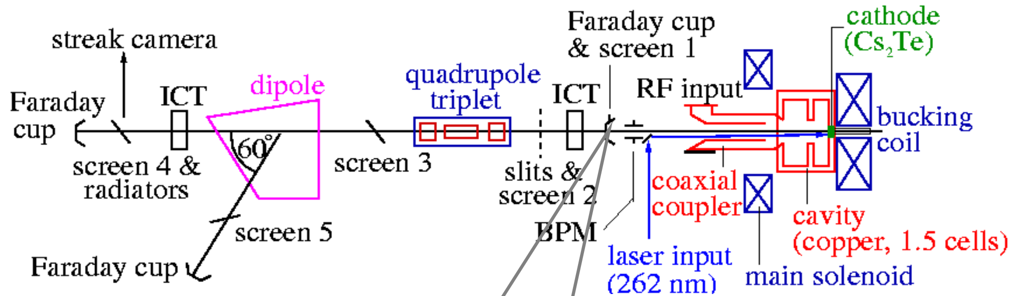
- rf pulse lenght: **900 μs**
- repetition rate: **10 Hz**
- gradient: **40 MV/m at the cathode** (~ 3 MW)

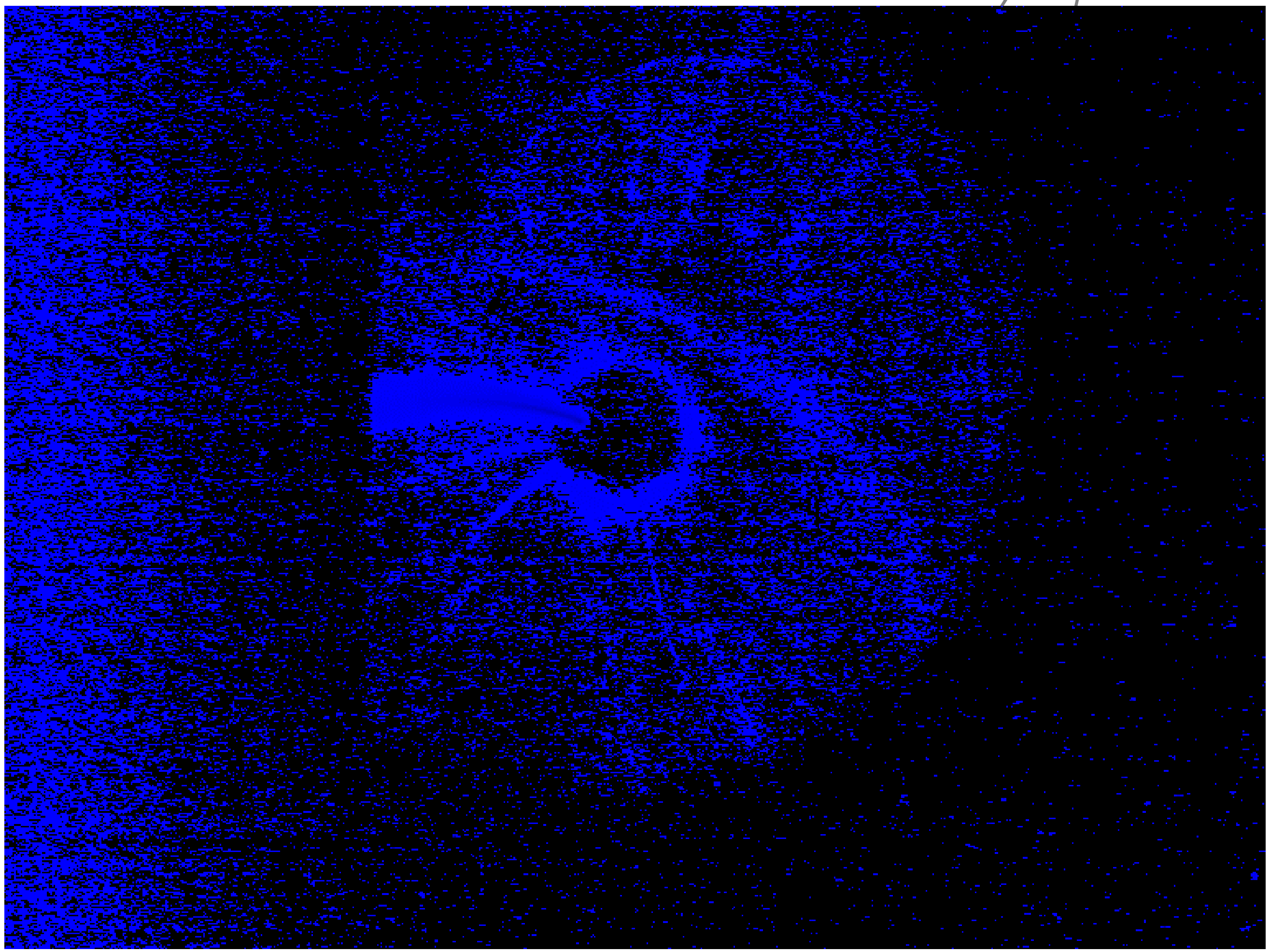
⇒ duty cycle: 0.9 %, average rf power: 27 kW

fulfills VUV-FEL RF parameter requirements

RF Gun Conditioning: Dark Current Studies

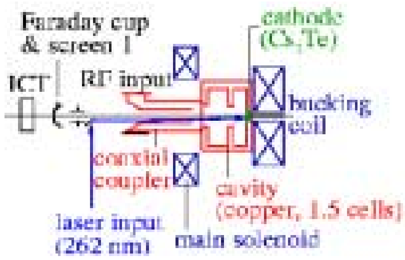
The **field emission** **of electrons from the cathode area is the main source of dark current.**



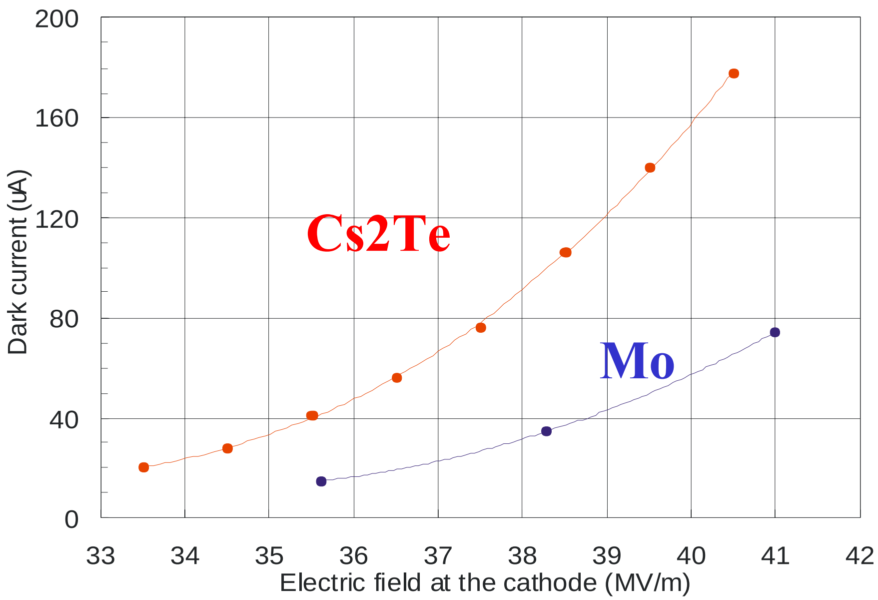


RF Gun Conditioning: Dark Current Studies

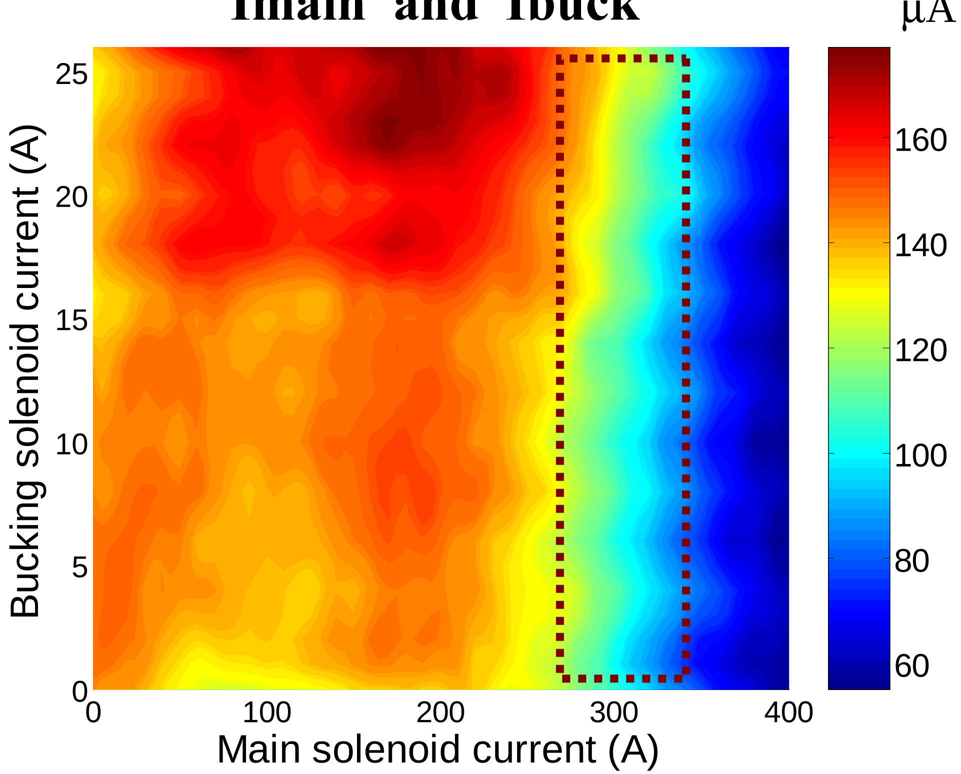
Dark current (DC) has been measured with a Faraday Cup at first Diag.Cross (~86 cm from the cathode) for various settings of the solenoid fields at the rf gun



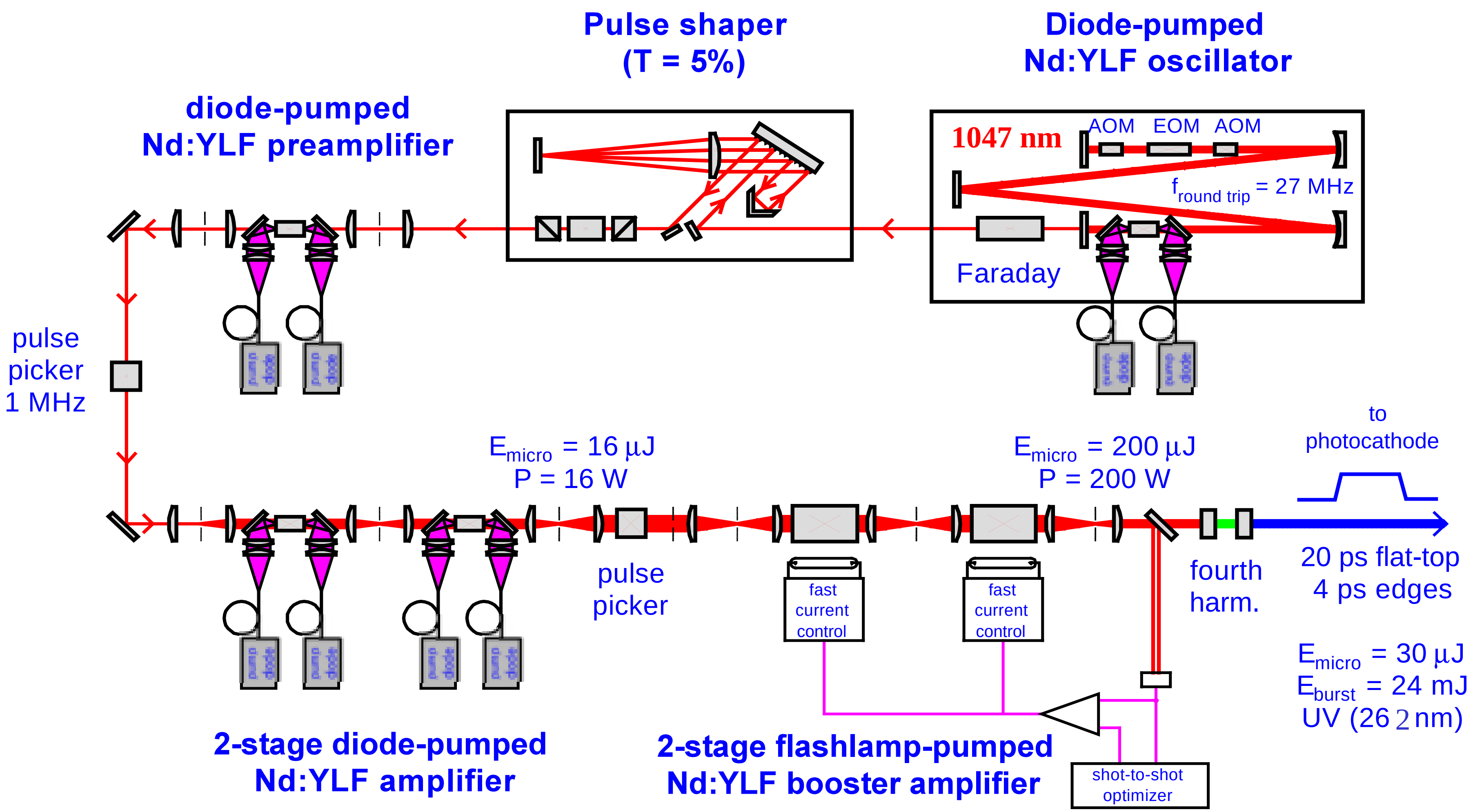
Maximum Dark Current vs Accelerating Field



DC (Cs_2Te, 40MV/m) vs Imain and Ibuck

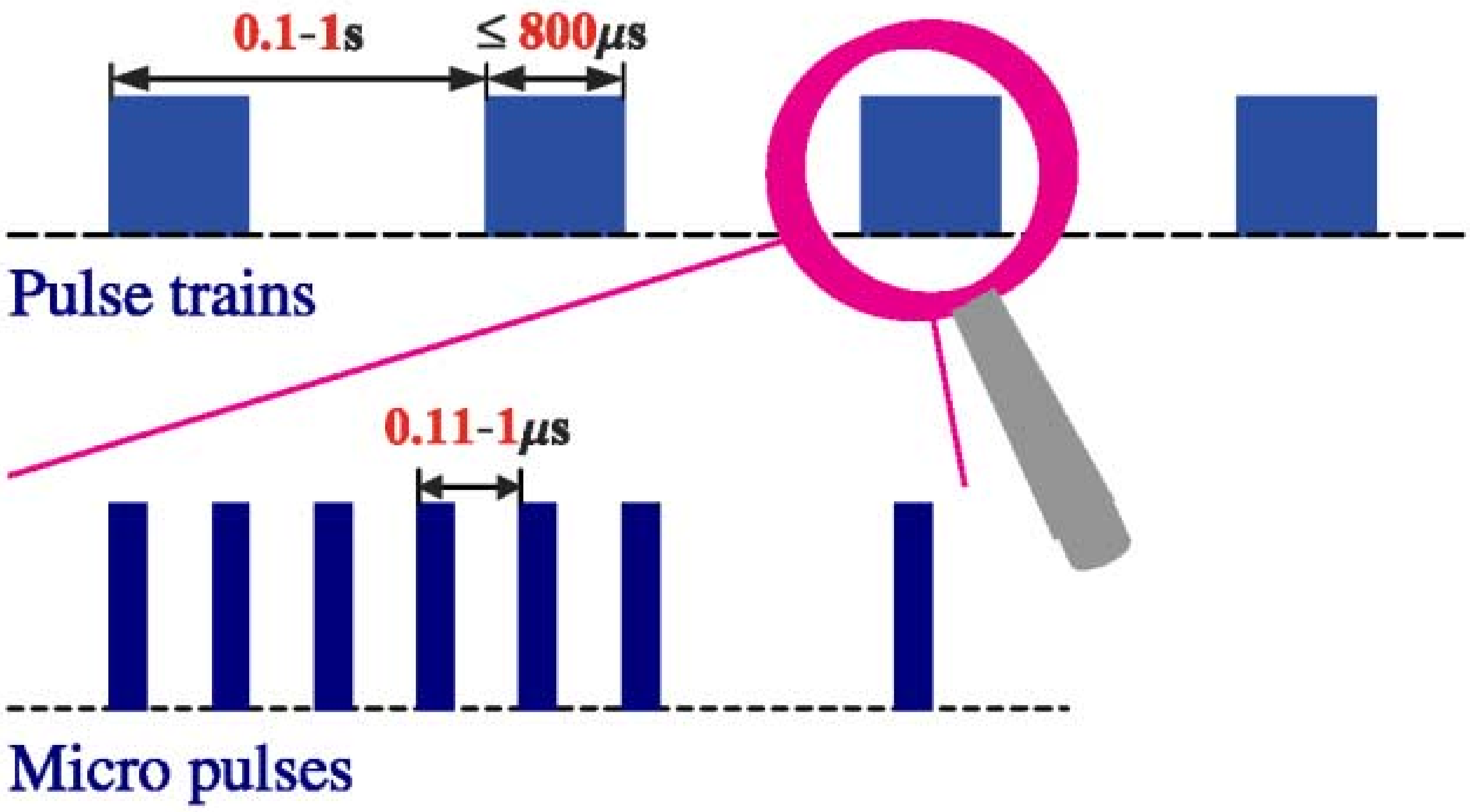


Photocathode Laser System (MBI)



Synchronization with RF!

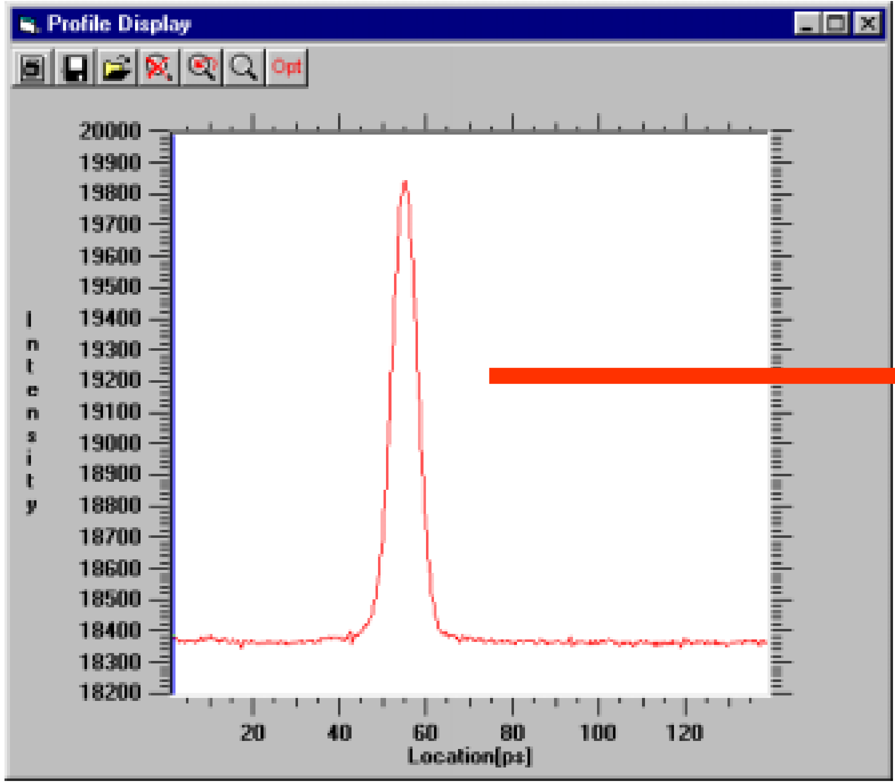
Photocathode Laser Pulse Structure

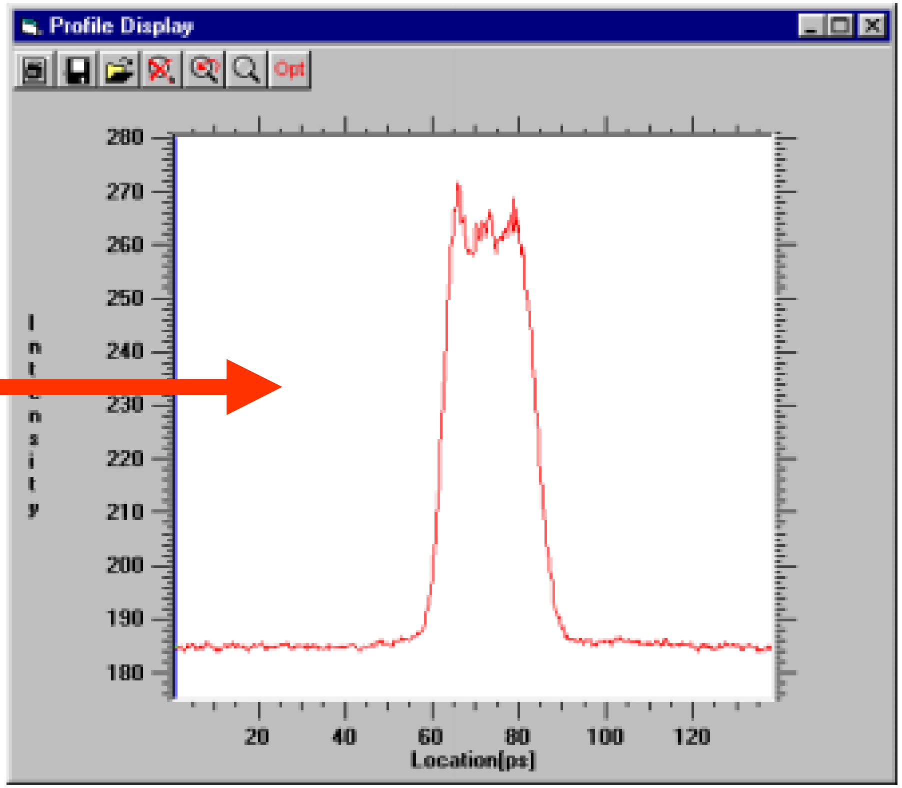


Micro Pulse Profile

Until 23.06.2003 - Gaussian longitudinal laser shape:

On 23.06.2003 longitudinal shape changed to flat top
=>reduced transverse emittance



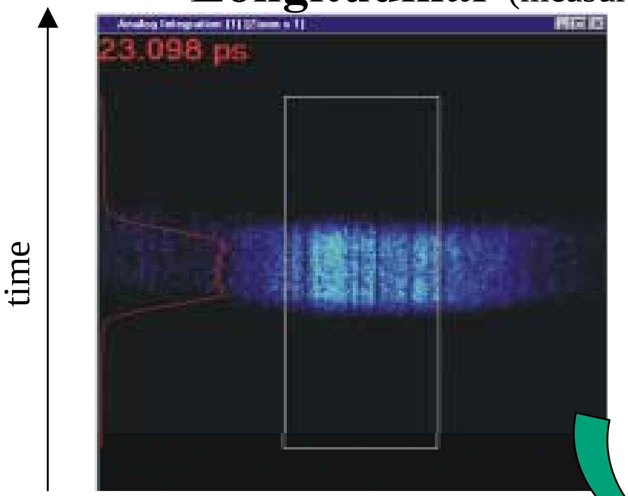


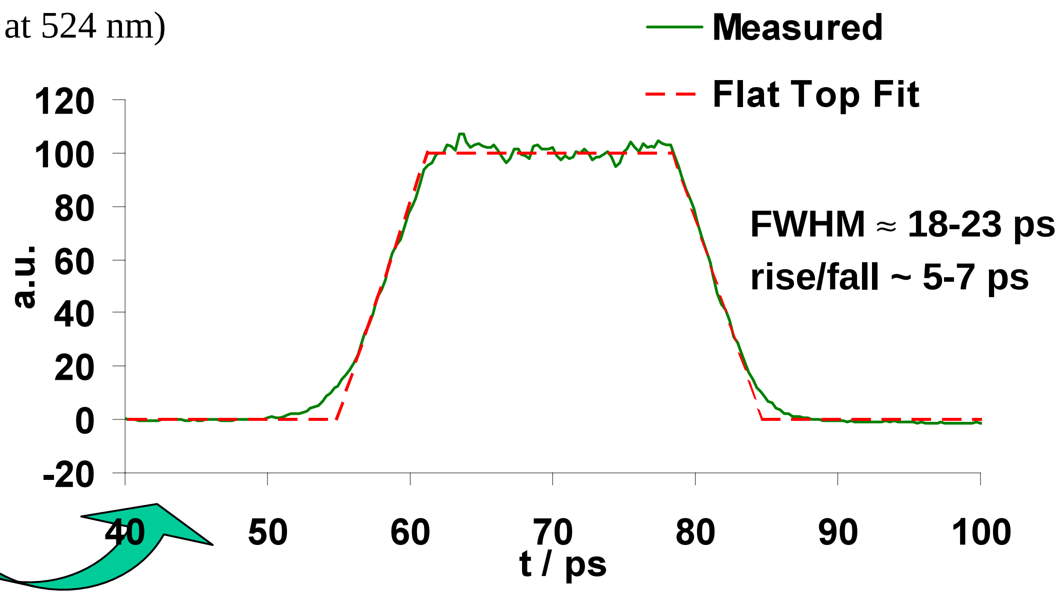
FWHM = 7 ± 1ps

FWHM ≈ 18-23 ps
rise and fall time about 5-7 ps

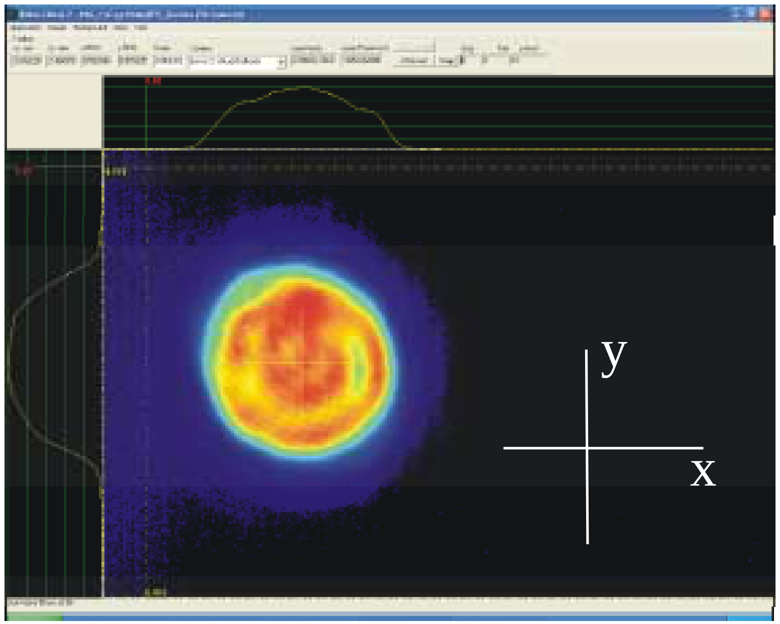
Longitudinal and Transverse Laser Profiles

Longitudinal (measured at 524 nm)





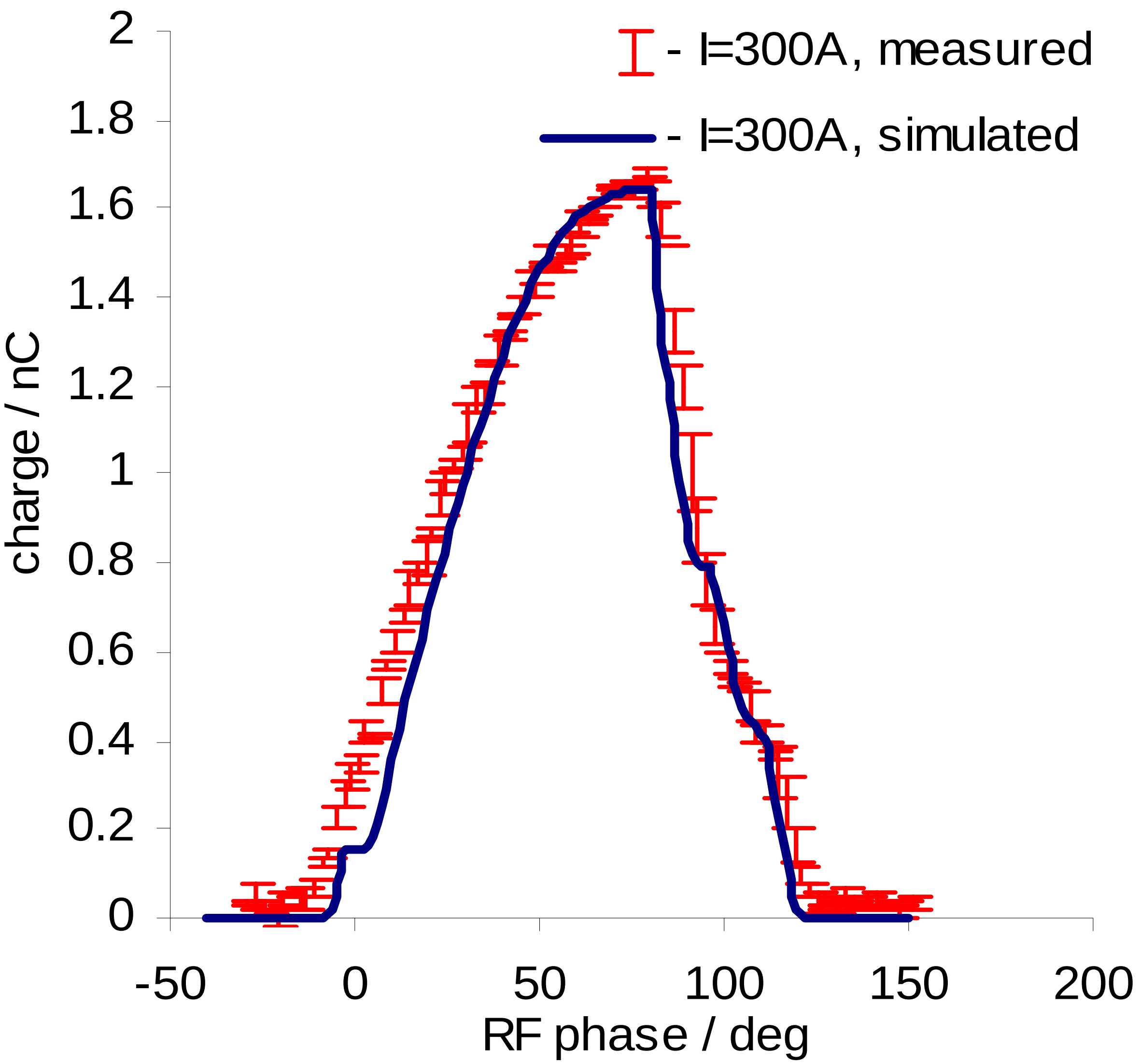
Transverse (measured in UV at virtual cathode)

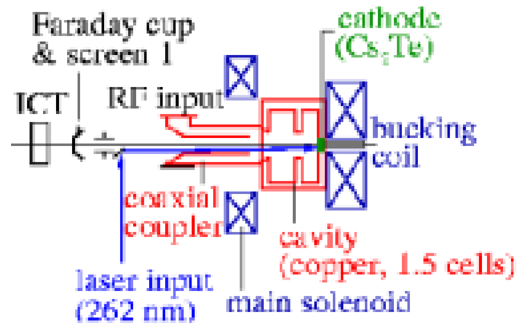


- **variable (RMS 0.3 – 1.0 mm)**
- **diaphragm is imaged on cathode**
- **e.g.:** $\sigma_x = 0.45\,\mathrm{mm}$
  $\sigma_y = 0.52\,\mathrm{mm}$

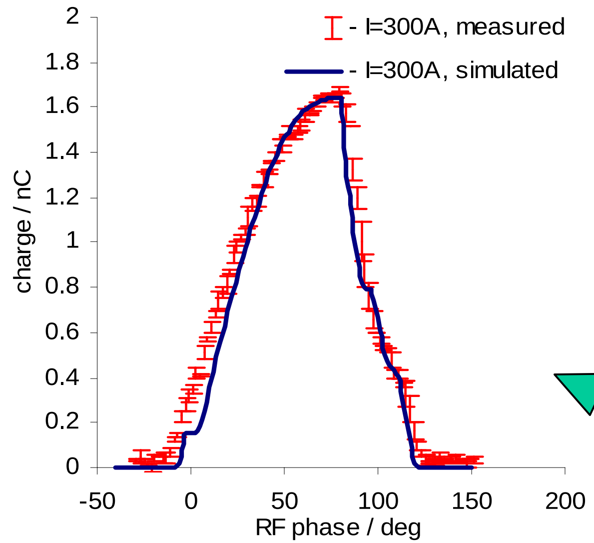
Beam Charge Measurement

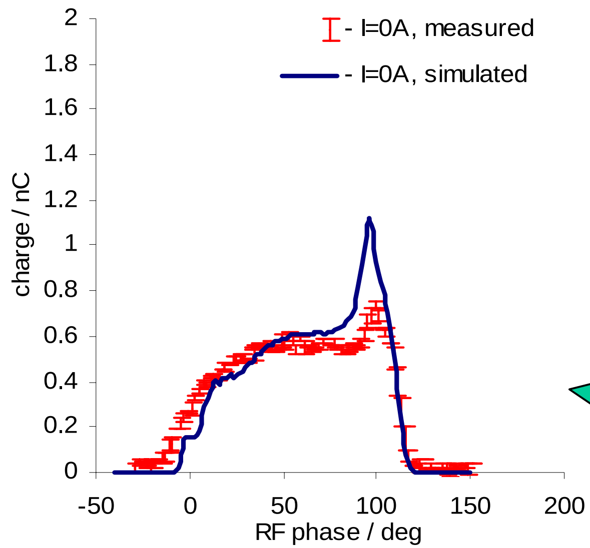
Phase Scan – Dependence of the Beam Charge on RF Phase

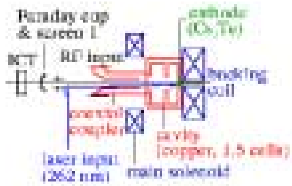




Phase Scan – Beam Charge Measurement

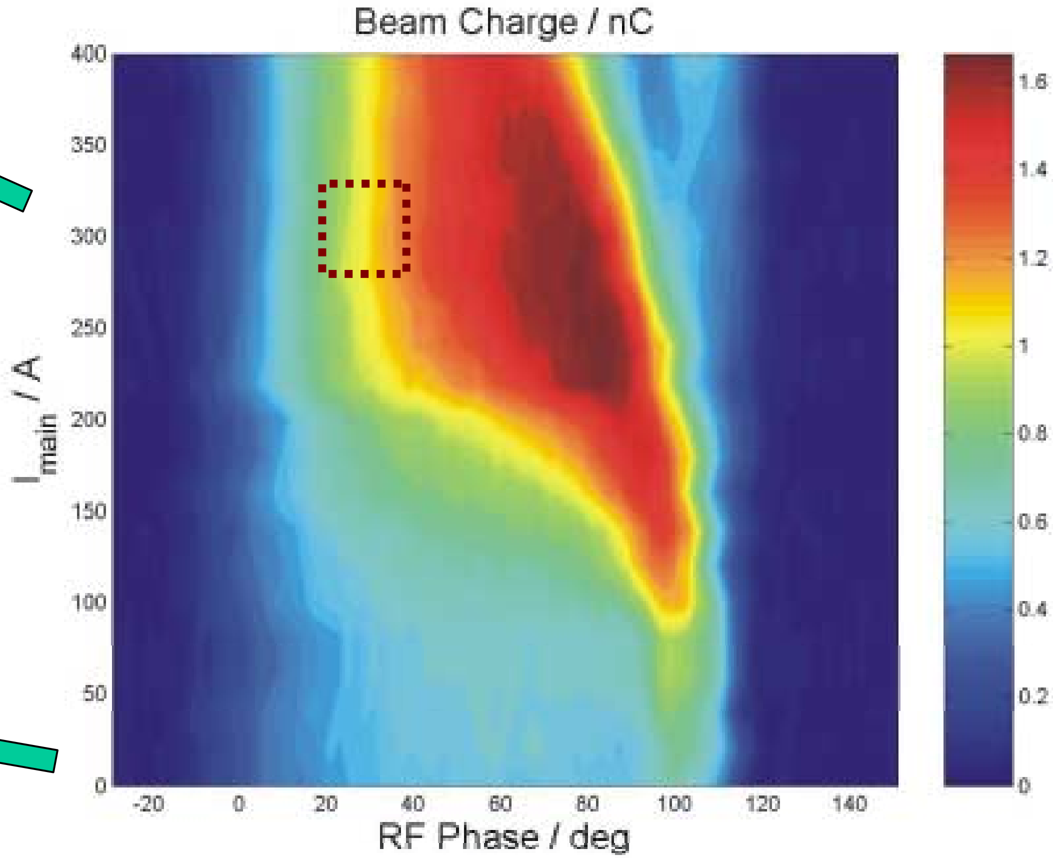






Measured 2D Phase Scan:

beam charge vs RF phase and Imain

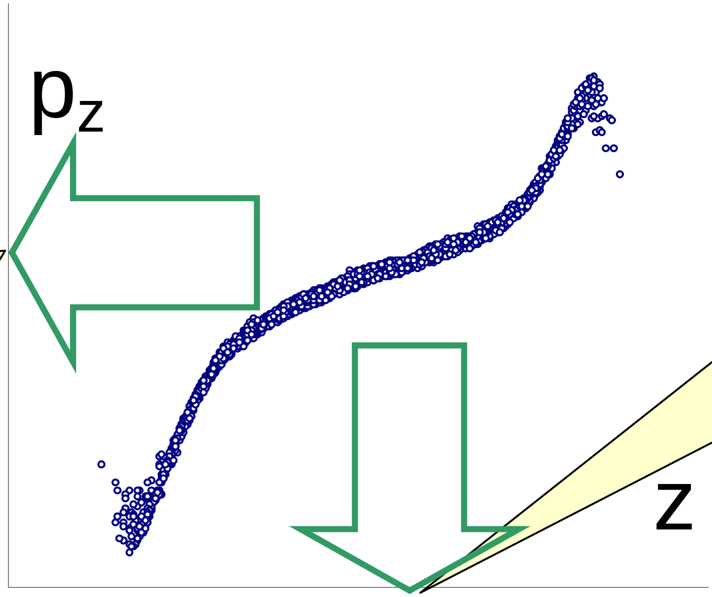


Apertures play significant role in charge transport

Longitudinal Phase Space (z, p_z)

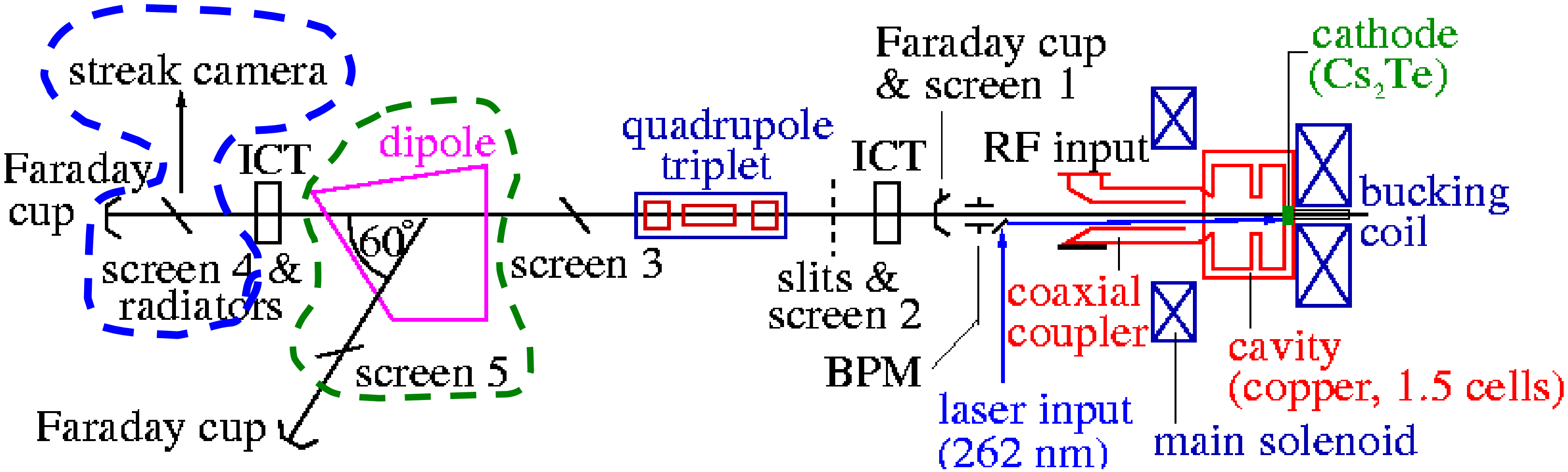
Momentum measurements

Tools: dipole spectrometer and screen 5

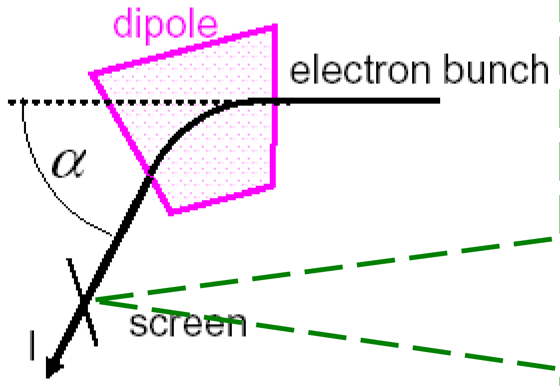


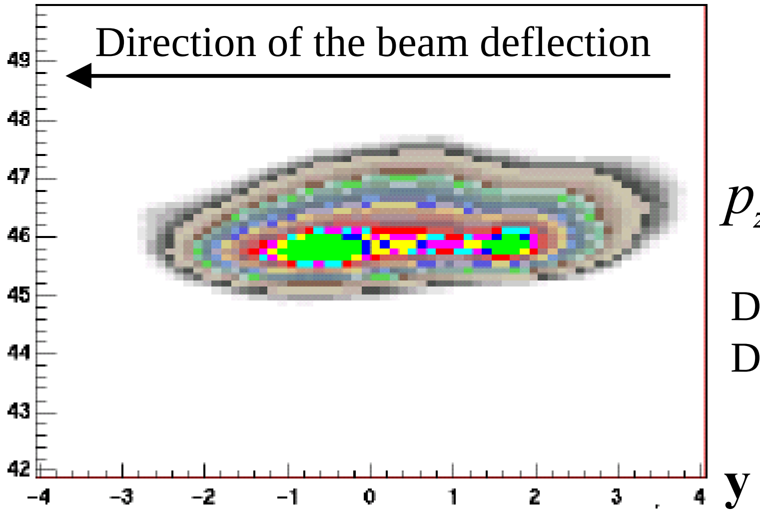
Bunch profile (length) measurements

Tools: Cherenkov radiators and streak camera



Longitudinal Momentum of the Electron Beam

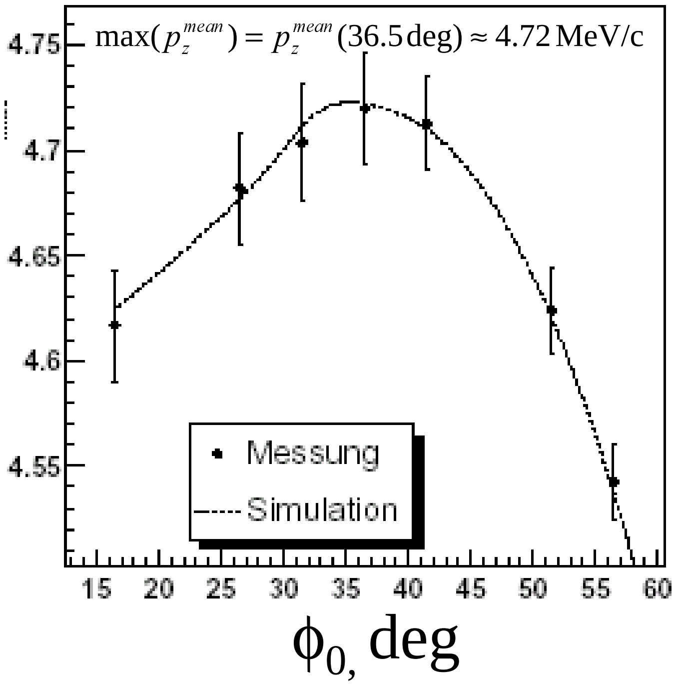




$$p_z = p_z^0 \cdot \left(1 + \frac{y}{D}\right)$$

Dispersion coefficient
D~770mm

Mean momentum vs RF phase



Charge 1 nC

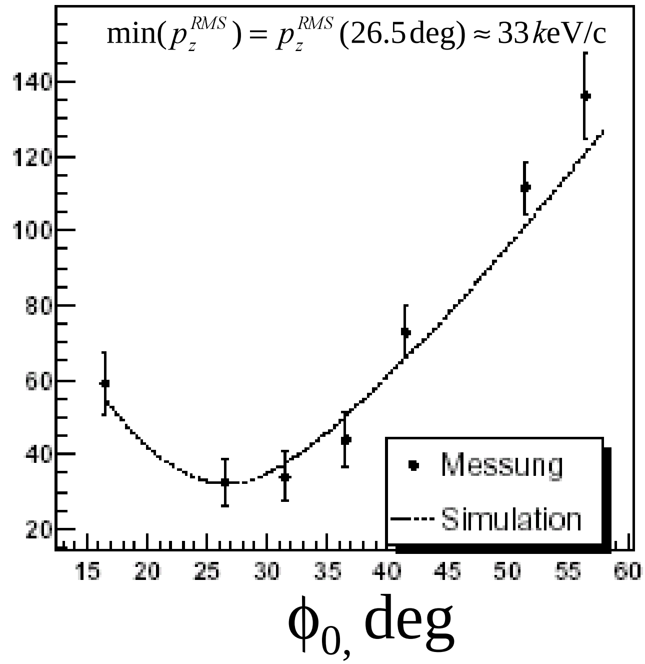
E_0~42MV/m

Laser: flat-top

I_{main}=280A

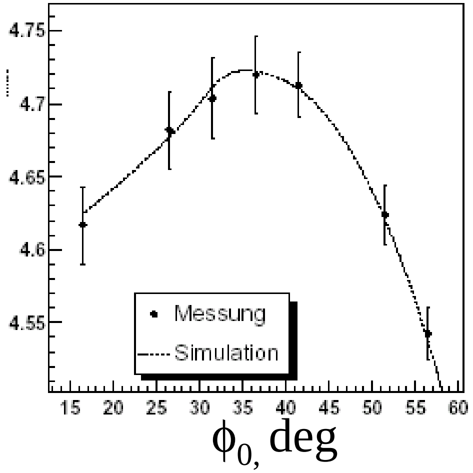
(B_{max}=165mT)

RMS momentum spread vs RF phase

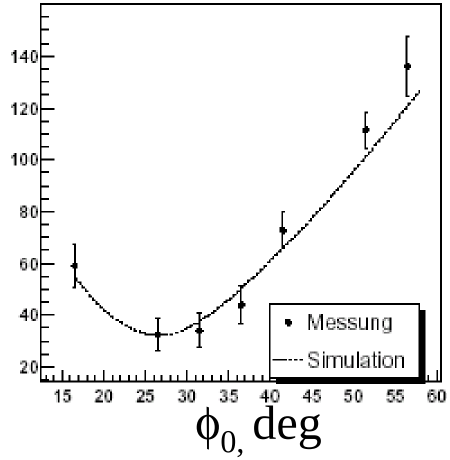


Longitudinal Momentum of the Electron Beam

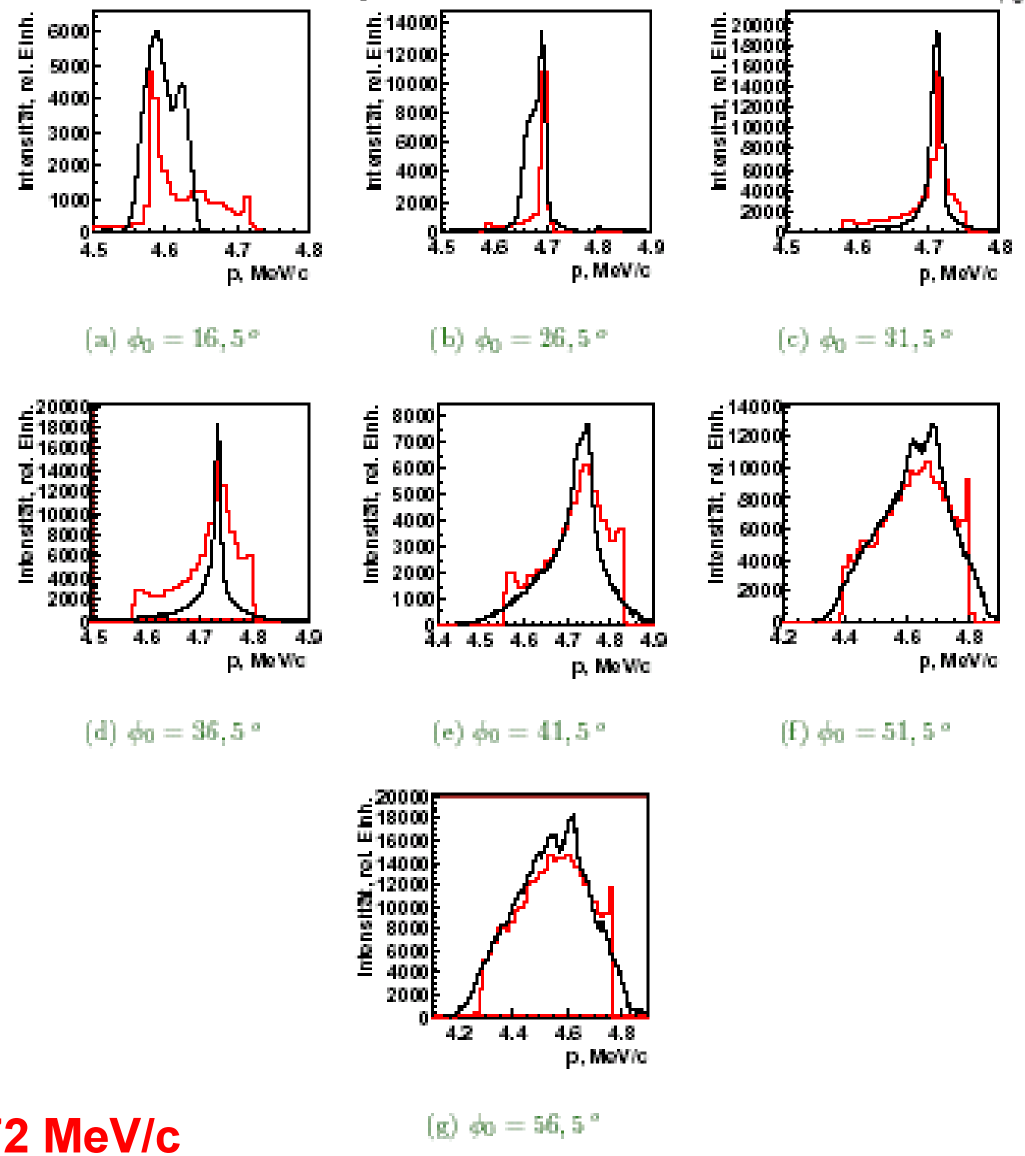
Mean momentum vs RF phase



RMS momentum spread vs RF phase



Measurement compared to simulation for different ϕ_0

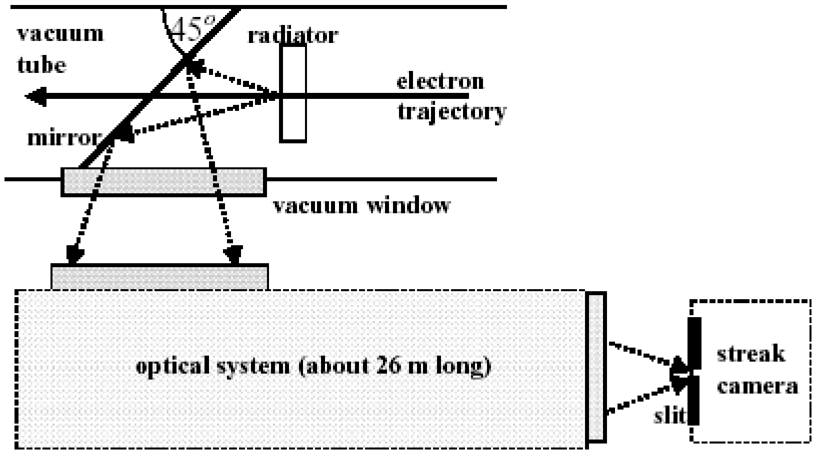


Maximum mean momentum 4.72 MeV/c

Minimum rms momentum spread 33 keV/c

Electron Beam Longitudinal Profile

PITZ1: Optimizing an Electron Source for FELs, *M. Krasilnikov, DESY 17.02.2004*

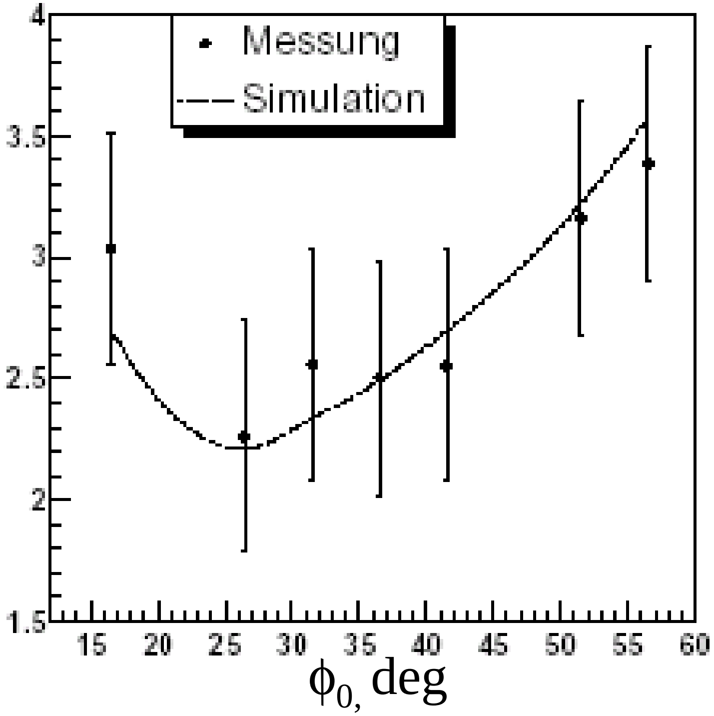


Cherenkov radiation

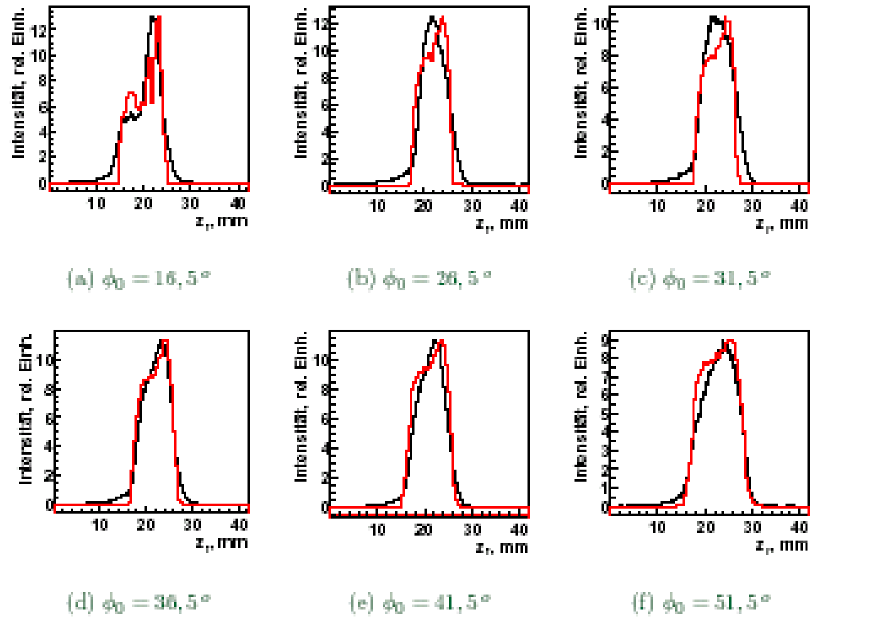
Use of **aerogel**: SiO2 ,

refractive index between 1.03

Bunch length (mm) in RMS 90 %:



Measurement compared to simulation for different ϕ_0



Minimum bunch length:

FWHM = (21.04 ± 0.45stat ± 4.14syst) ps

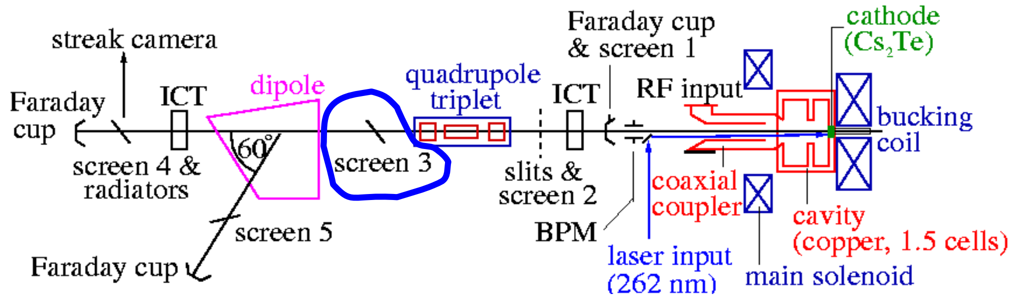
= (6.31 ± 0.14stat ± 1.24syst) mm

Reference RF Phase

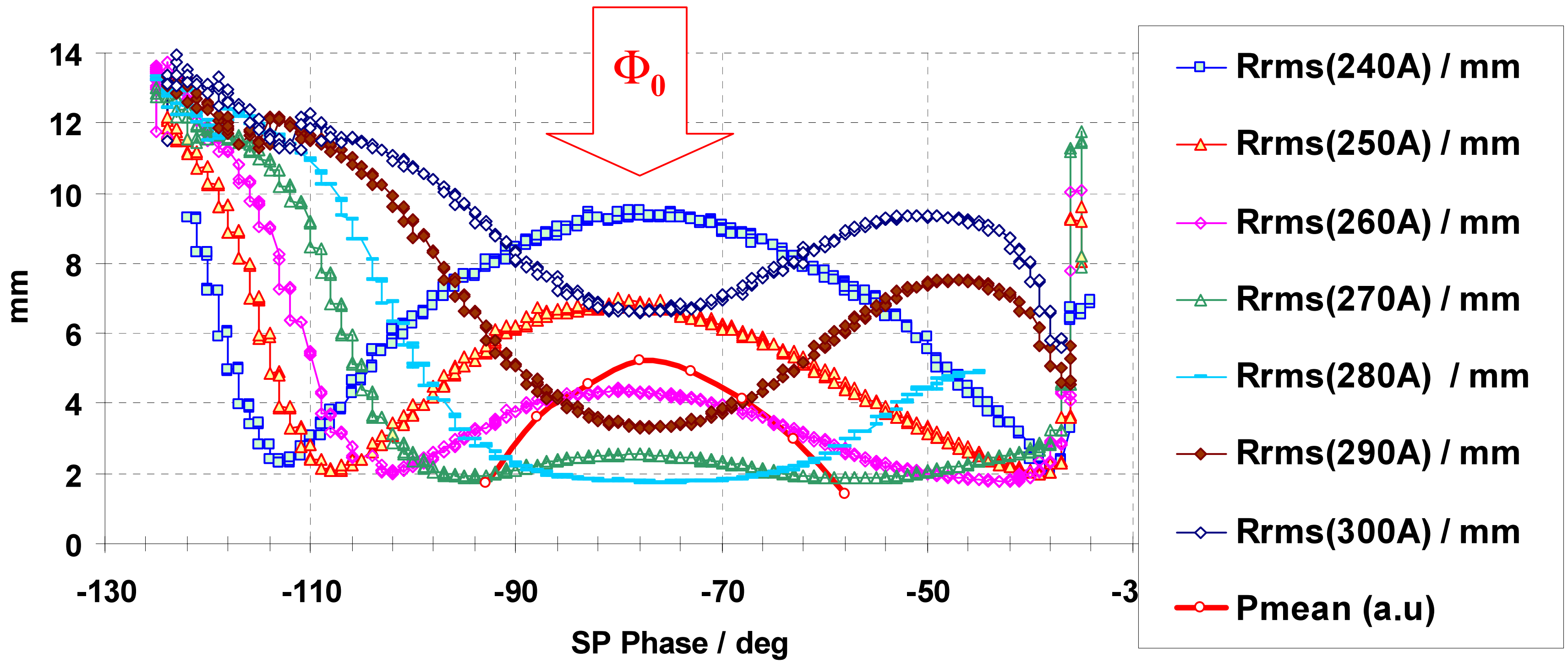
Set Point (SP) RF phase

?

RF phase with maximum mean energy gain Φ_0

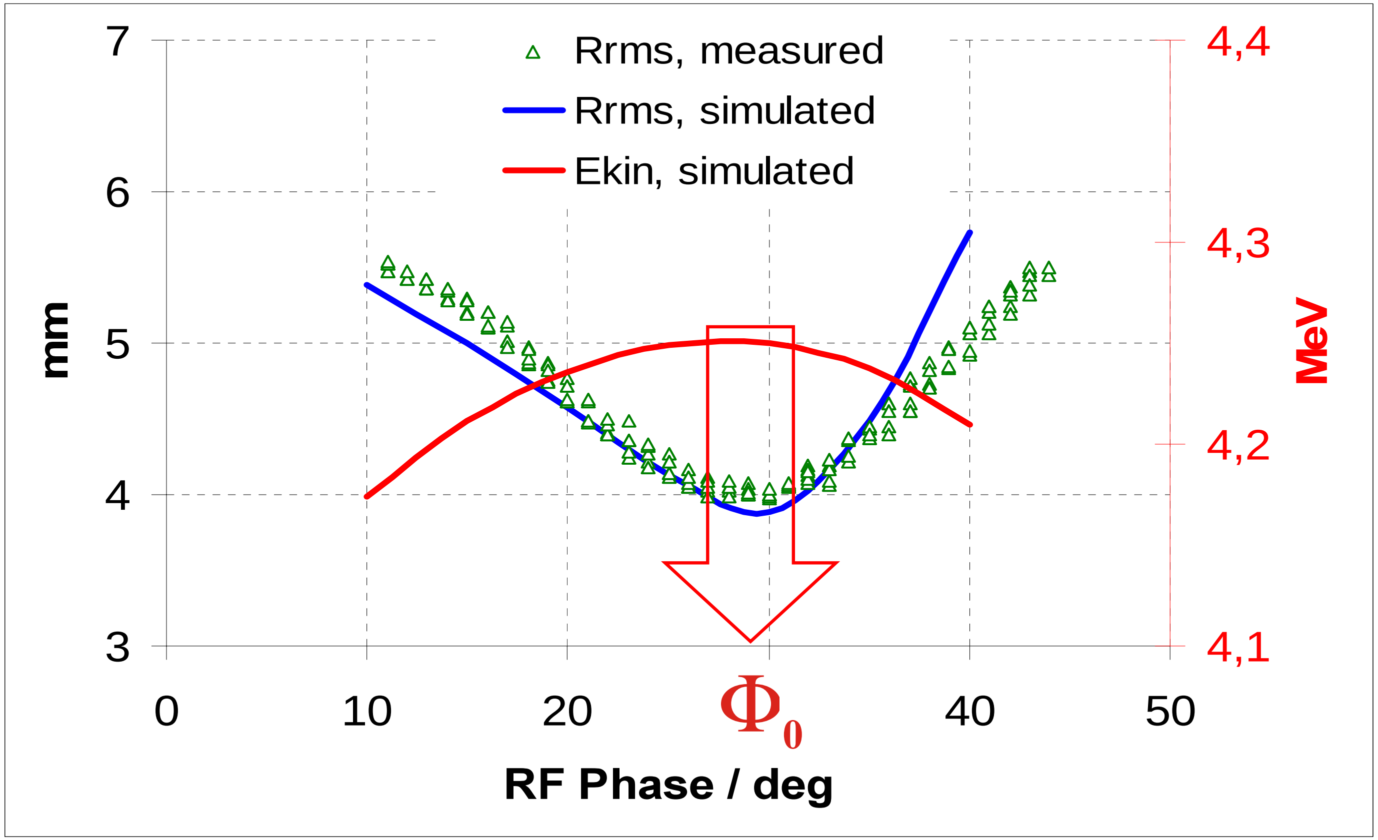


Transverse RMS Beam Size at Screen 3 as a Function of SP Phase for Different Main Solenoid Currents



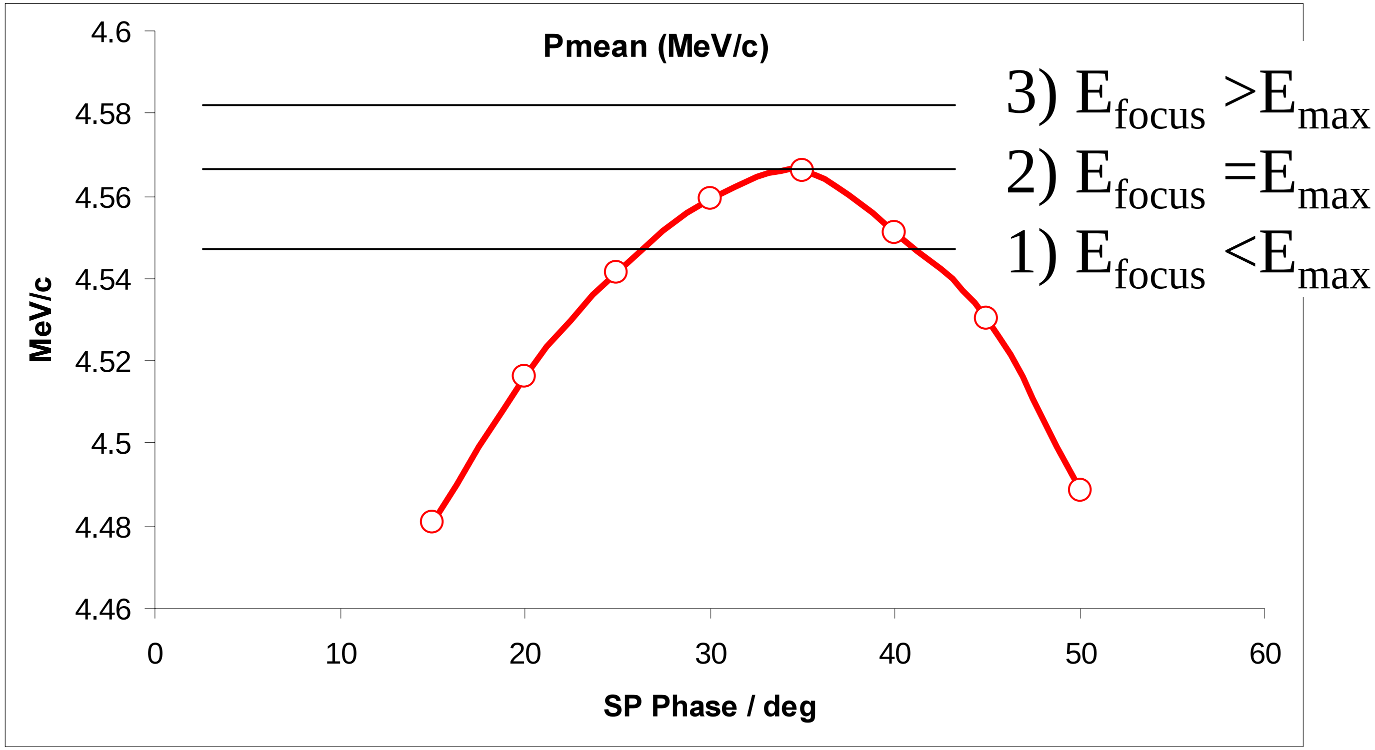
Reference RF Phase

Transverse RMS Beam Size at Screen 3 as a Function of SP Phase (Main Solenoid Current=300A)

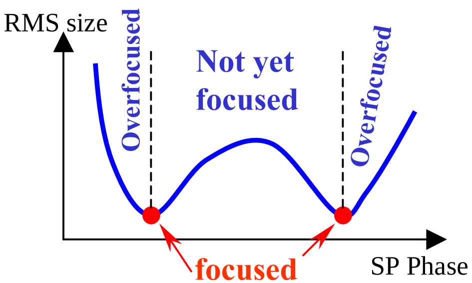


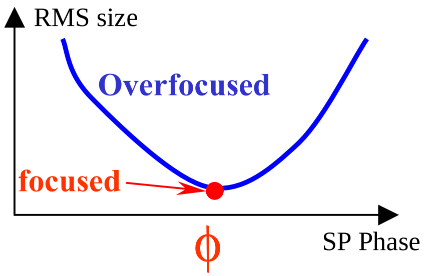
Method to Find Reference RF Phase

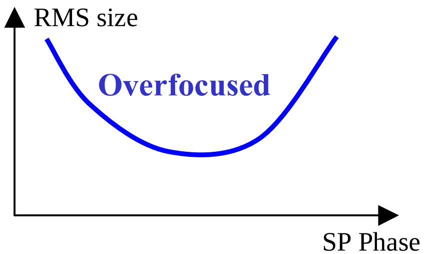
$I_{main} \rightarrow B_{eff} \rightarrow E_{focus}$ $\qquad$ $I_{main}(1) < I_{main}(2) < I_{main}(3)$



1) $E_{focus} < E_{max}$ $\qquad$ 2) $E_{focus} = E_{max}$ $\qquad$ 3) $E_{focus} > E_{max}$







Method:

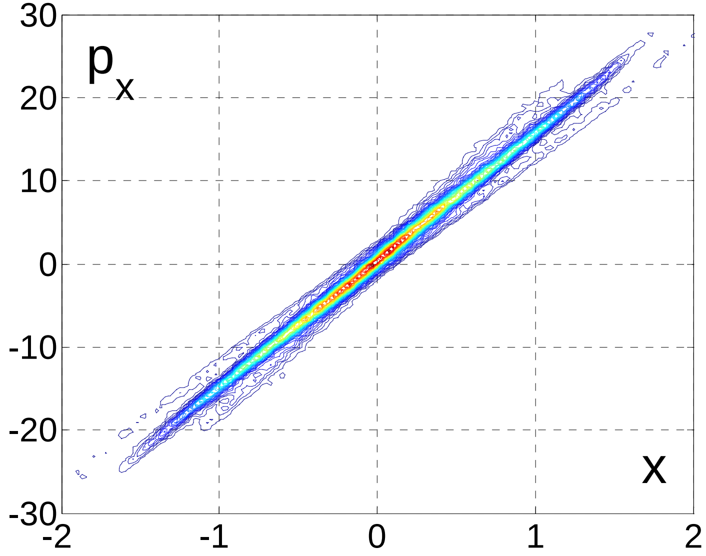
measure transverse RMS size of the electron beam as a function of SP Phase for definite solenoid current.

- **easy**
- **quick**
- **reliable**

Transverse Beam Emittance

Normalized beam emittance

$$\varepsilon_{nx} = \beta\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$



Beam Emittance Measurements

Method:

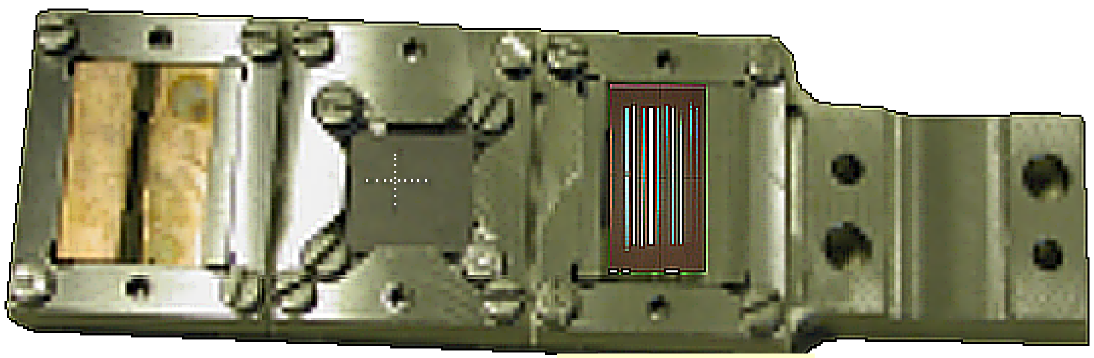
- **Quadrupole scan** (transfer matrix elements reconstruction)
- **Slit-mask technique** ("direct" divergence measurement)
- …

Beam transverse size measurements:

- **Using screen**
- **Wire scanner**
- …

Main method for the emittance measurement at PITZ is

Slit-Mask Technique+Screen

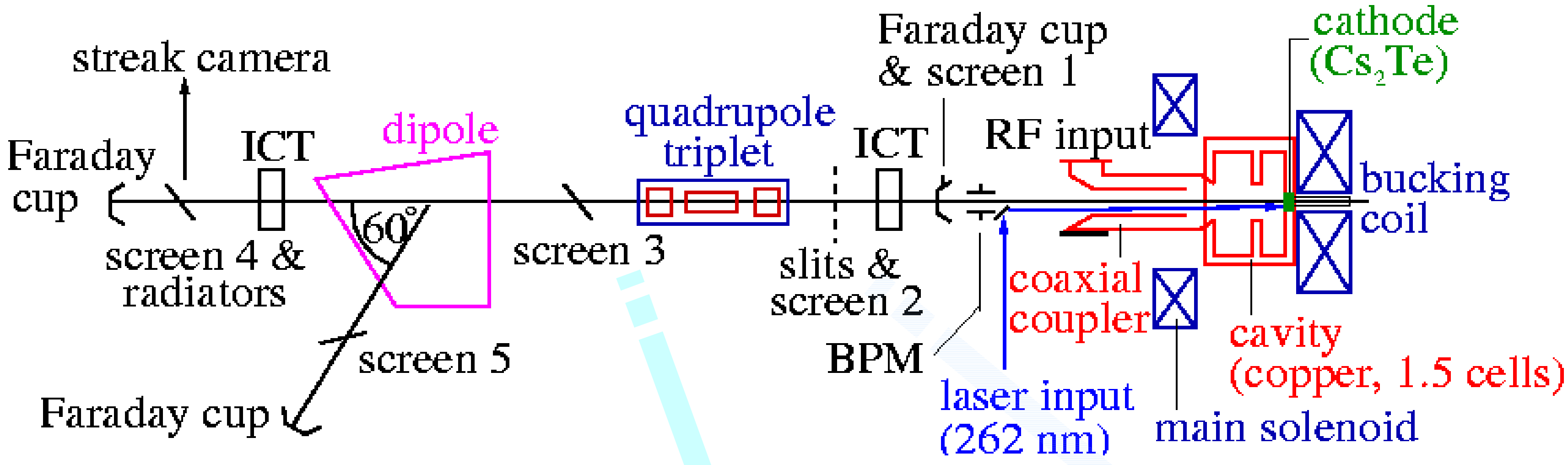


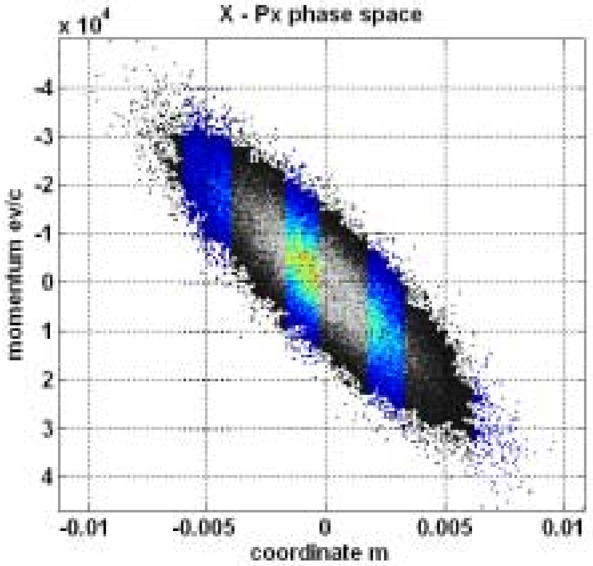
Single Slit: 50µm

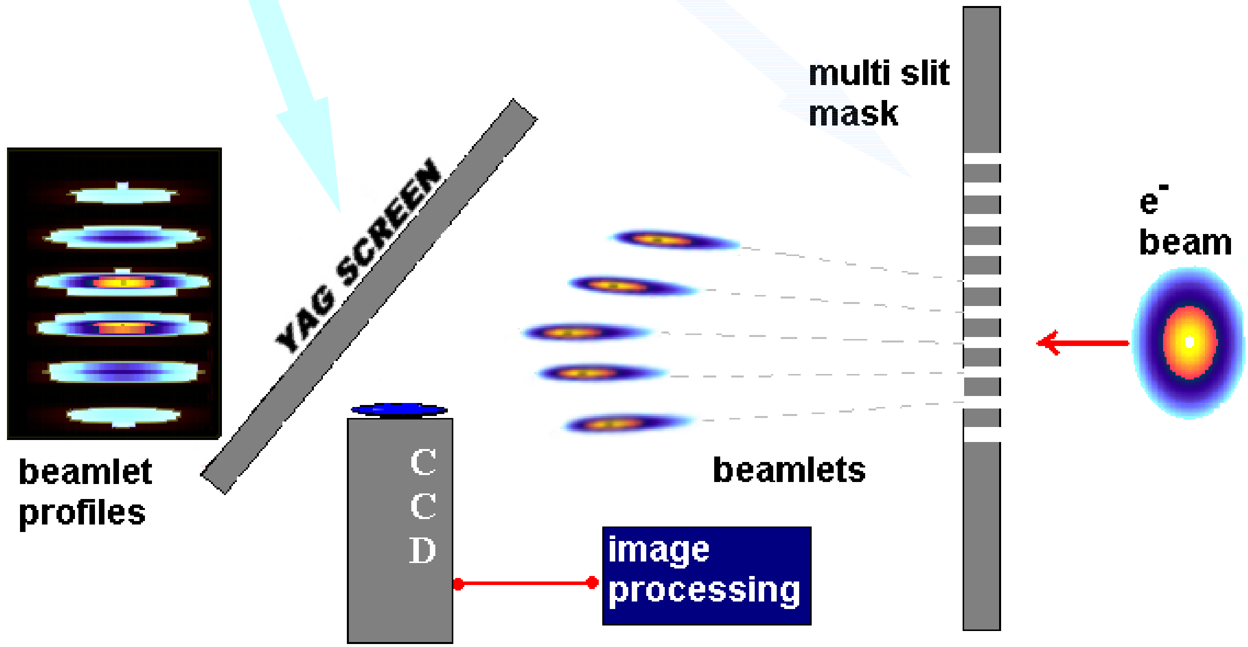
Pepper-Pot: 50µm x 0.8mm

Multi-Slit: 25µm x 1mm

Transverse Beam Emittance Measurement

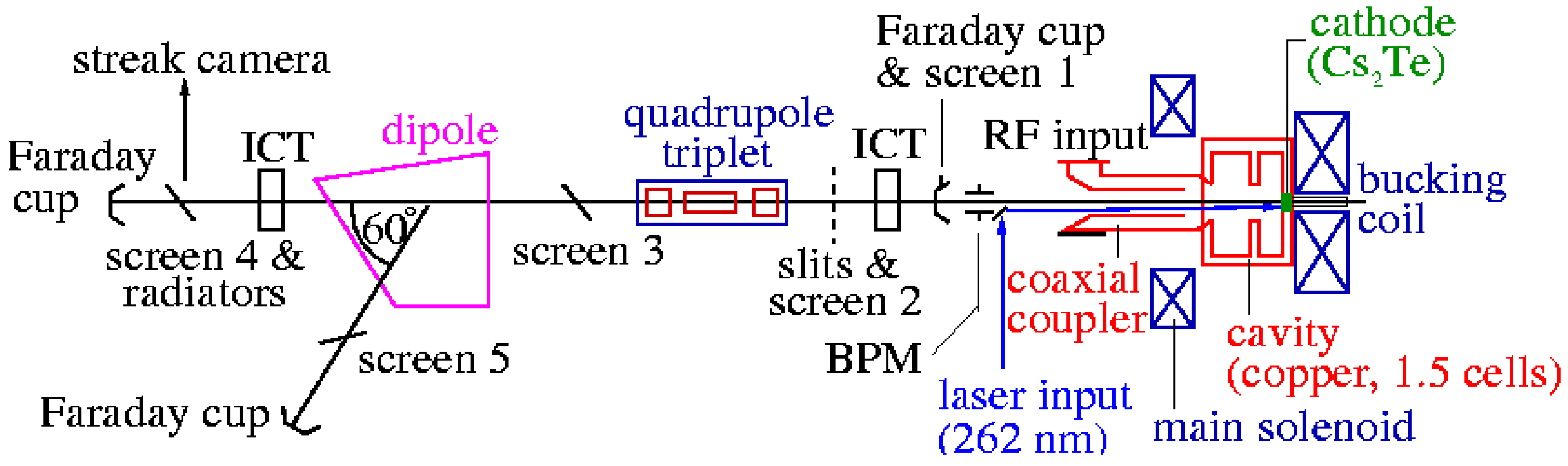






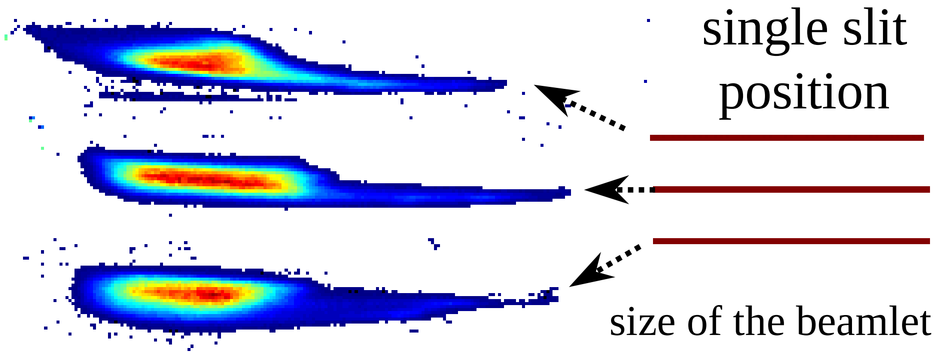
But: ➡ •beamlets overlapping •small beam size ➡ **single slit scan**

Transverse Beam Emittance Measurement

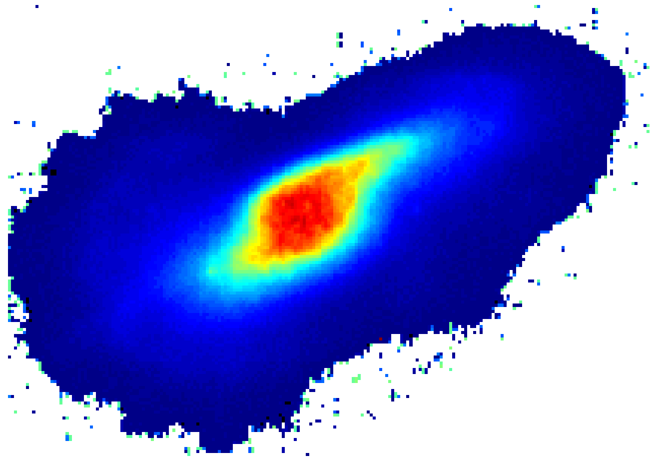


Single Slit Scan Technique

Beamlets at screen 3



Beam spot at screen 2

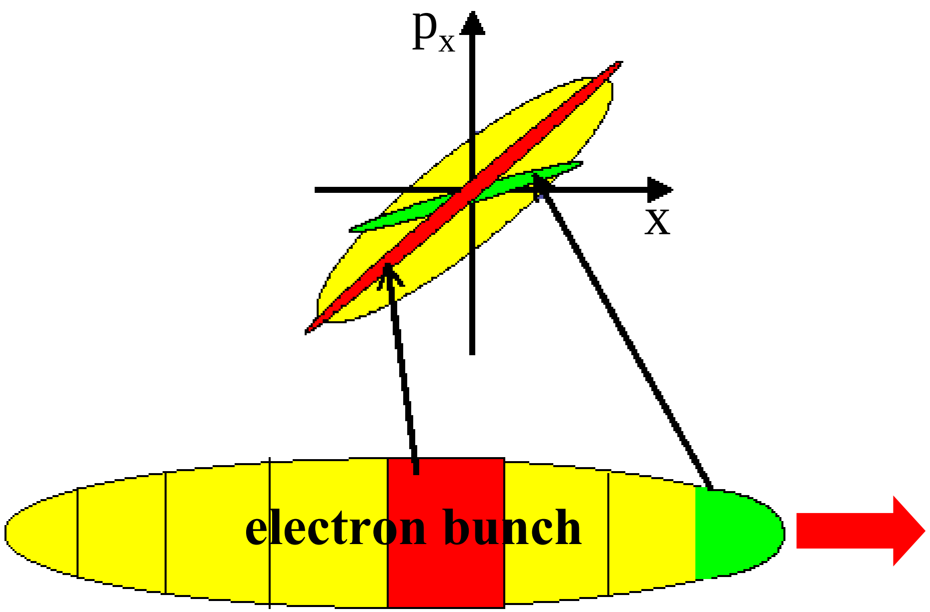


size of the beamlet is measured for three slit positions:

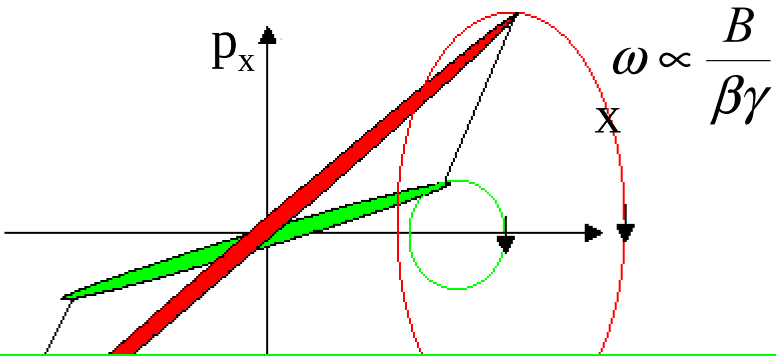
$$y_n = \langle Y \rangle^{screen\,2} + n \cdot 0.7\sigma_y^{screen\,2}$$

$$n \in \{-1,0,1\}$$

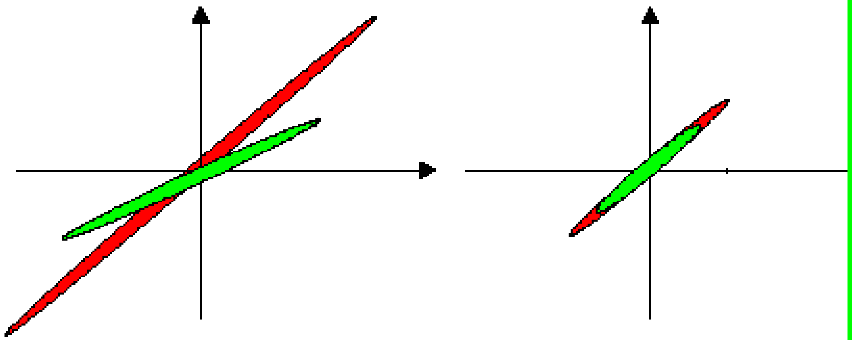
Slice and Projected Emittance



In solenoid magnetic field



By choosing optimal parameters



Longitudinal laser profile

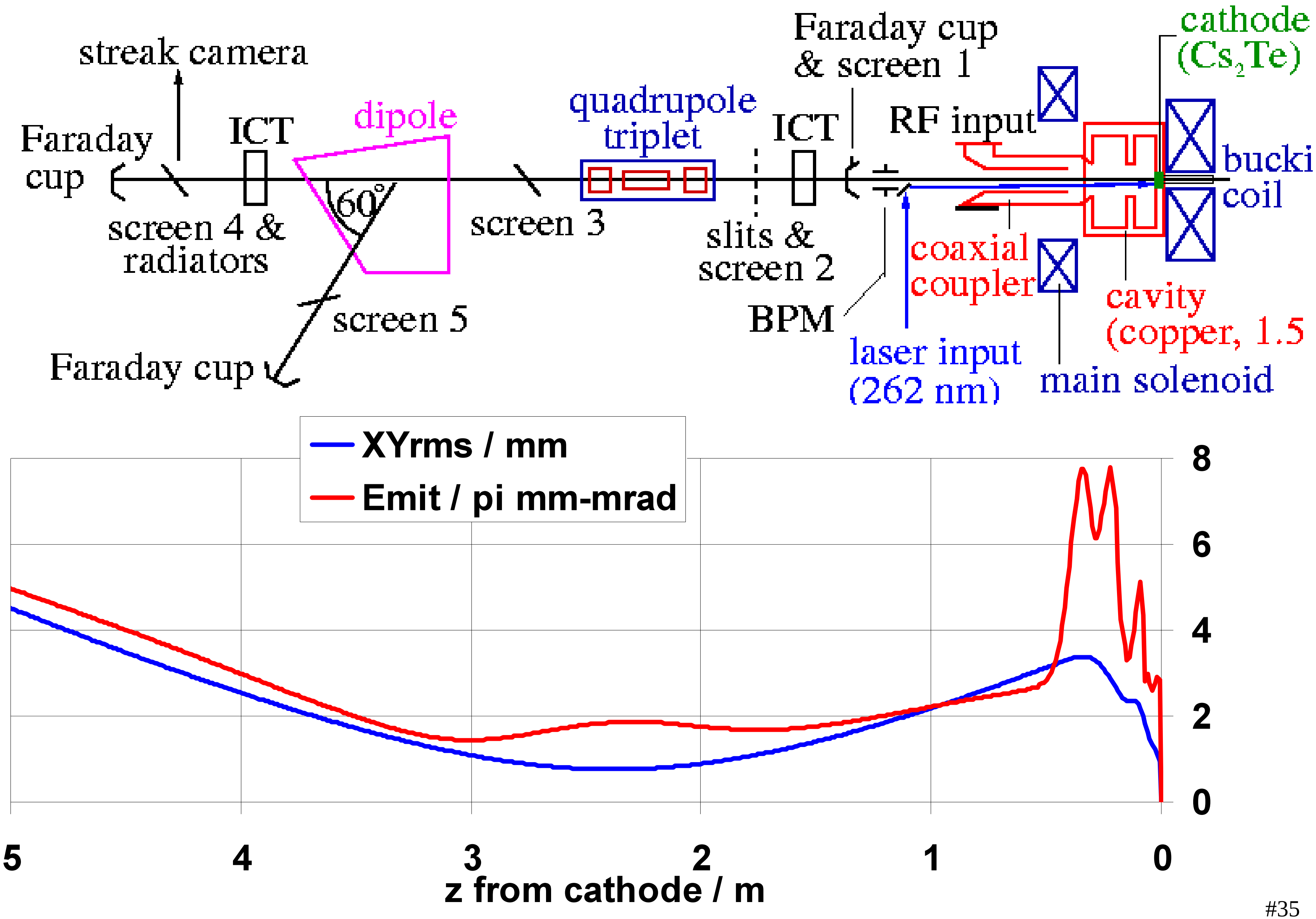
Laser spot size on the cathode

Emittance scan (RF Phase, Imain)

↓

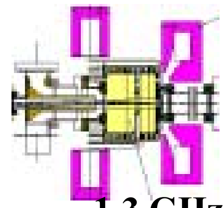
Bucking solenoid tuning (Ibuck)

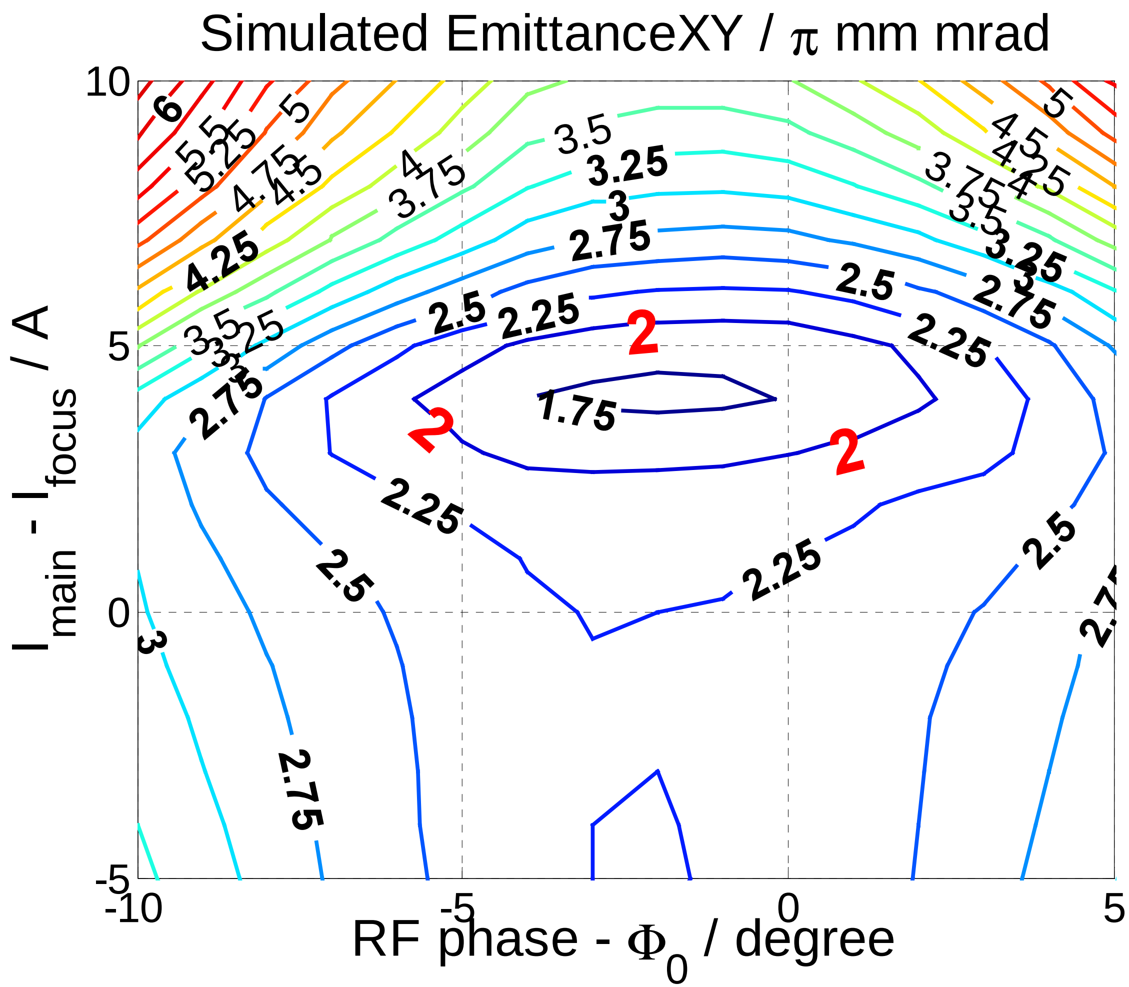
Transverse Beam Size and Emittance



Simulated Transverse Emittance

ASTRA Simulation:





Parameters used for the simulation:

- **charge** = 1 nC
- **longitudinal laser profile**:
  – flat top
  – 20 ps FWHM
  – 5 ps rise/fall time
- **transverse laser profile**
  – homogeneous
  – $\sigma_{x,y}$ = 0.6 mm
- **max. gradient at the cathode**: 42 MV/m

Transverse Emittance Measurements

Running conditions:

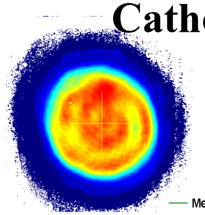
~ 40 MV/m at the cathode

1 nC charge (re-adjusted for each RF phase)

RF phase: -10 . . . +10 deg. around F_0

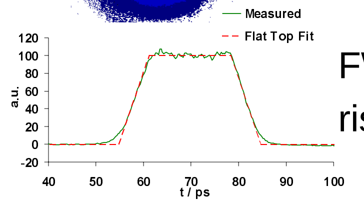
main solenoid current: 295 A … 310 A (focus at screen 2: 300A)

Cathode laser D=1.2mm



$$\sigma_x = 0.45 \pm 0.03 mm$$

$$\sigma_y = 0.52 \pm 0.03 mm$$

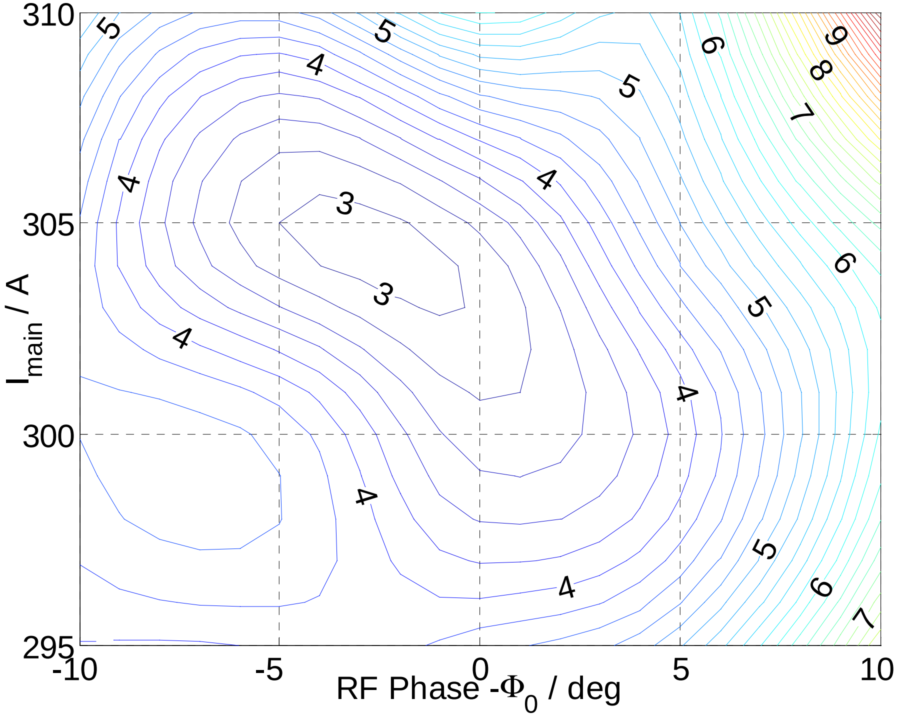


FWHM ≈ 20 ps

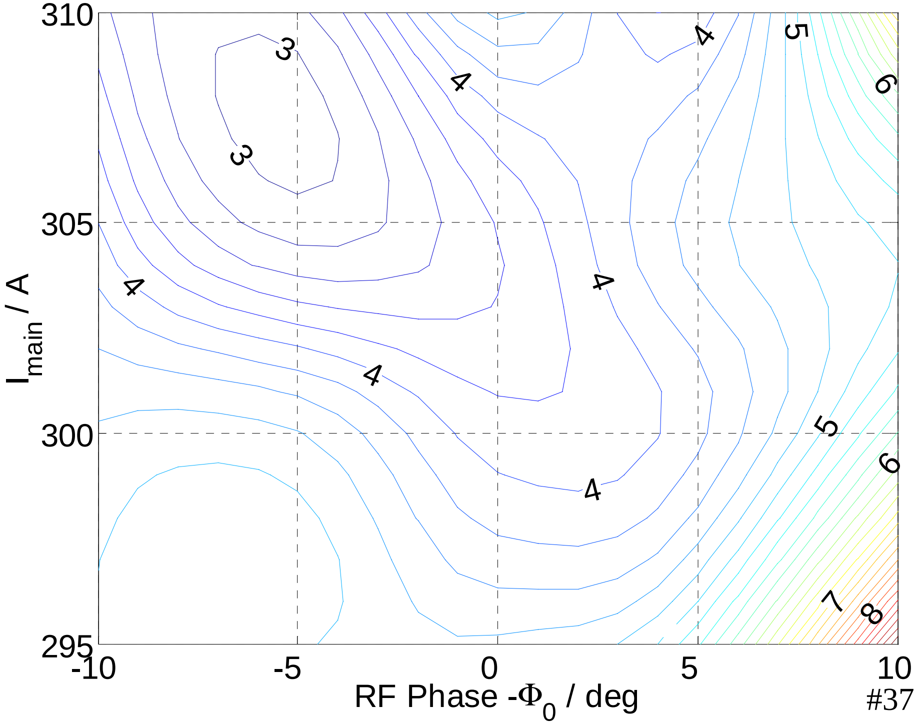
rise/fall ~ 5 ps

Measured Normalized Emittance as a Function of RF Phase and Main Solenoid Current

Measured EmittanceX / π mm mrad

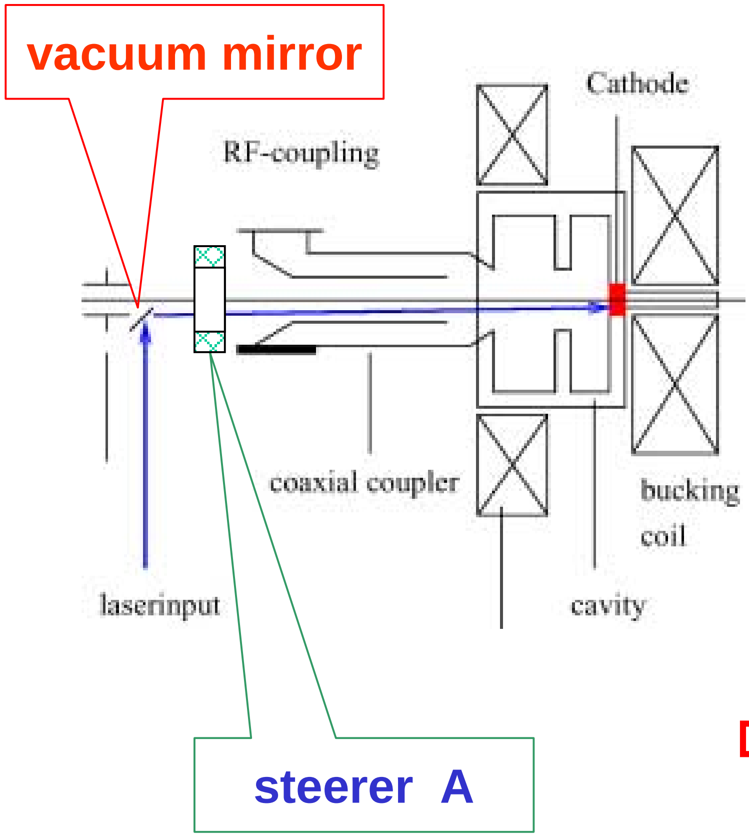


Measured EmittanceY / π mm mrad

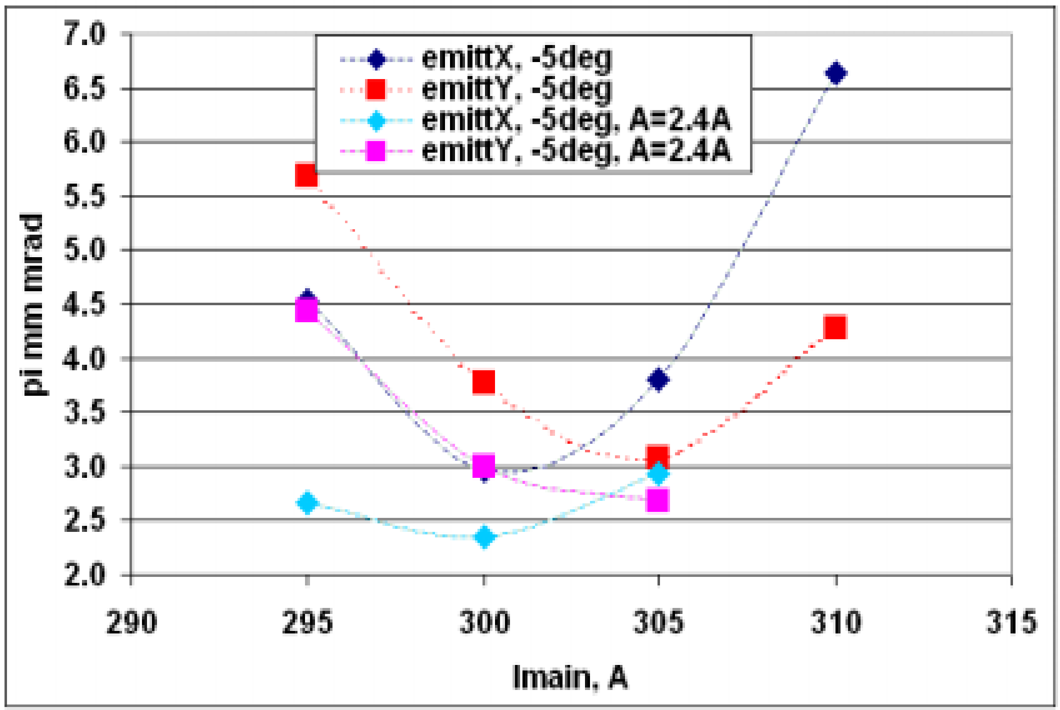


Steps to improve Beam Emittance

- status in Sept. 2003: min. emittance " 3 π mm mrad
- improvement: steer beam away from vacuum mirror



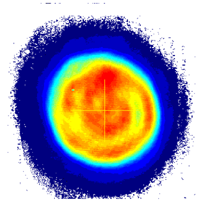
1 nC, D = 1.2 mm



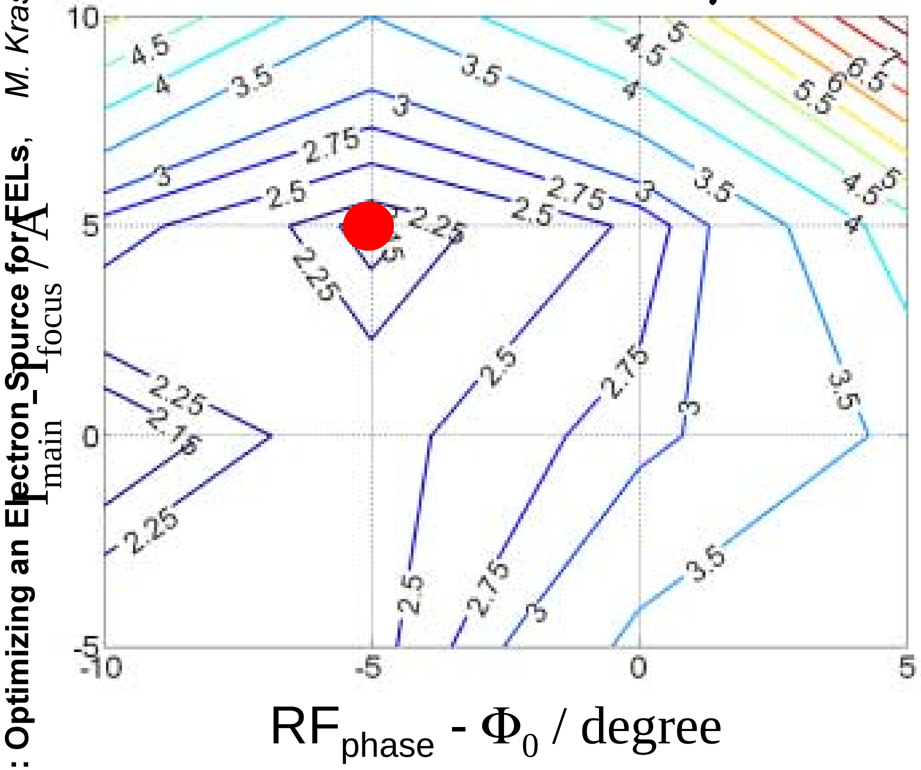
⇒ improvement: > 0.5 π mm mrad

Transverse Emittance Measurements

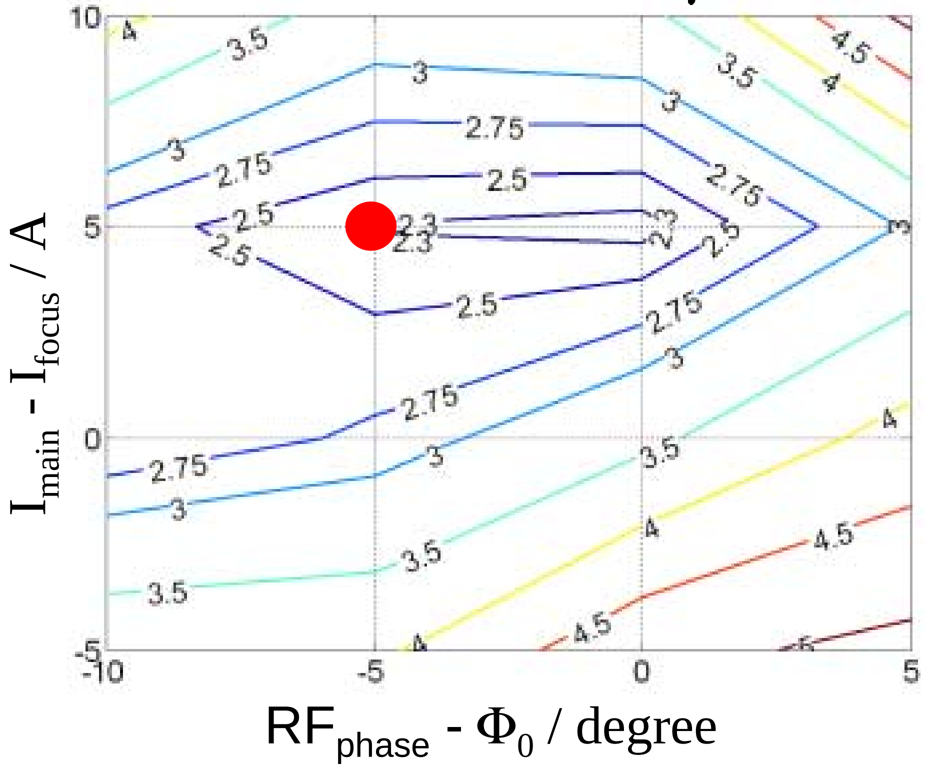
Parameters: 1 nC, ~20 ps FWHM, ~7ps rise/fall time, diaphragm = 1.2 mm



norm. emittance X / µm

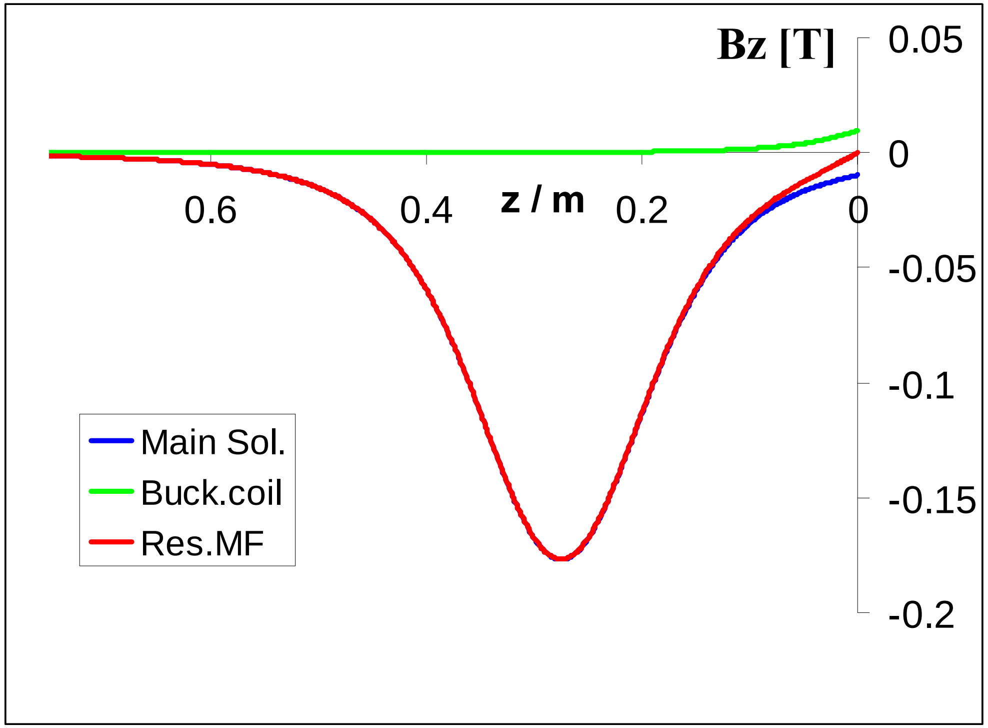


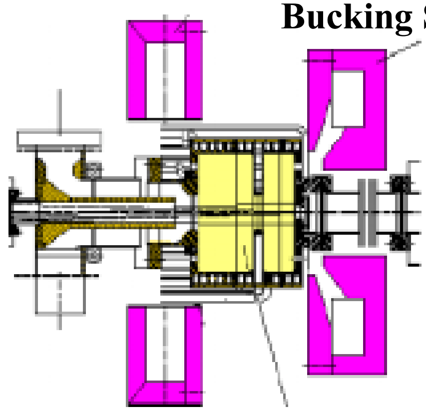
norm. emittance Y / µm



Transverse Emittance Measurements

Bucking Solenoid Influence





$$\varepsilon_n^{magnetic} = \frac{e}{2mc} B_z(z=0) \cdot \sigma_r^2$$

$I_{main} \approx 300\text{A} \Rightarrow B_z(z=0) \sim 0.01\text{T}$
$\sigma_r \sim 0.7$ mm
$\varepsilon_n^{magnetic} \approx 293 \cdot B_z(z=0) \cdot \sigma_r^2 / 2 \sim 0.65\pi\, mm\, mrad$

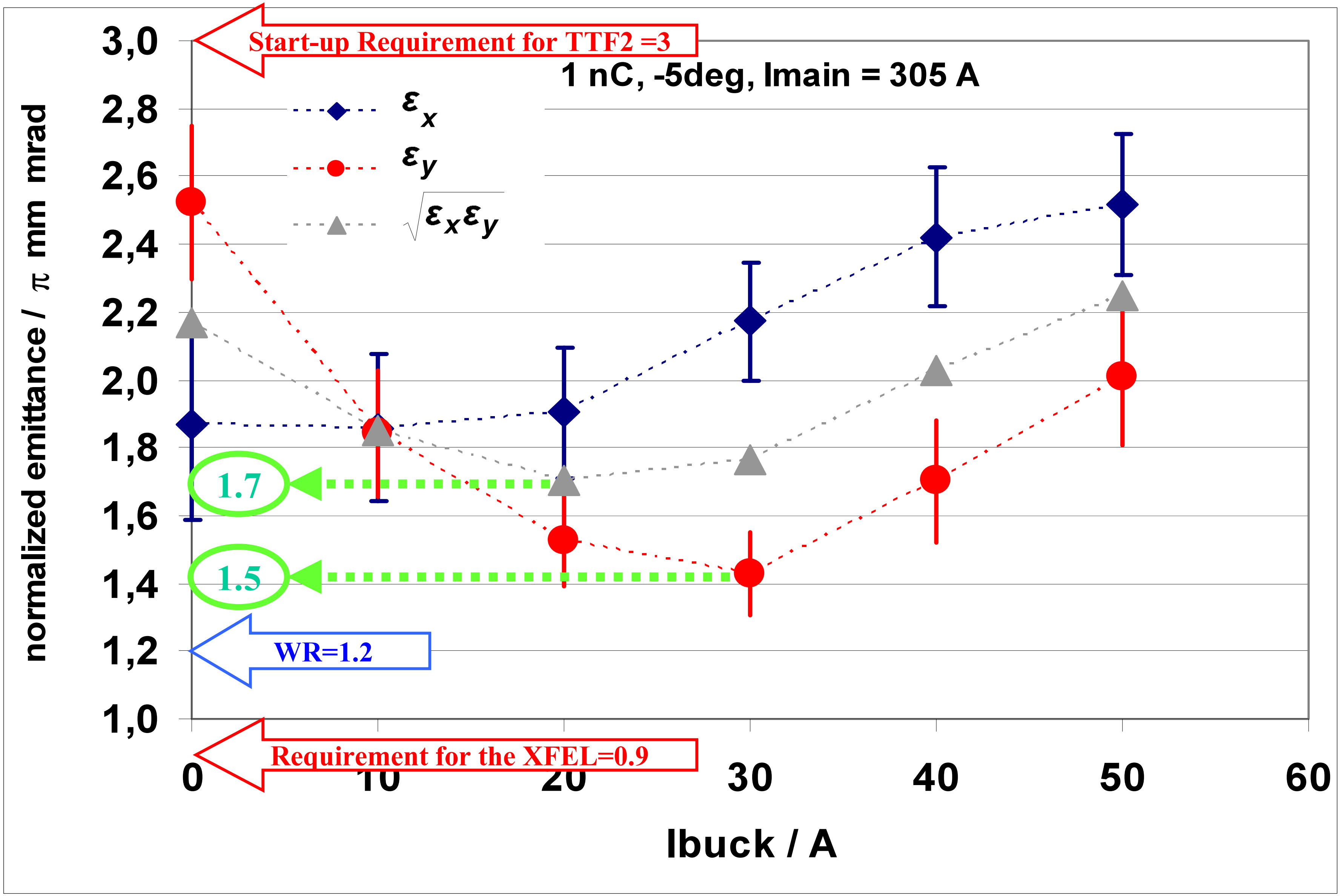
Fine emittance optimization – tune **bucking solenoid** for the best parameters

(RF Phase*, I_{main}*)

of the emittance scan

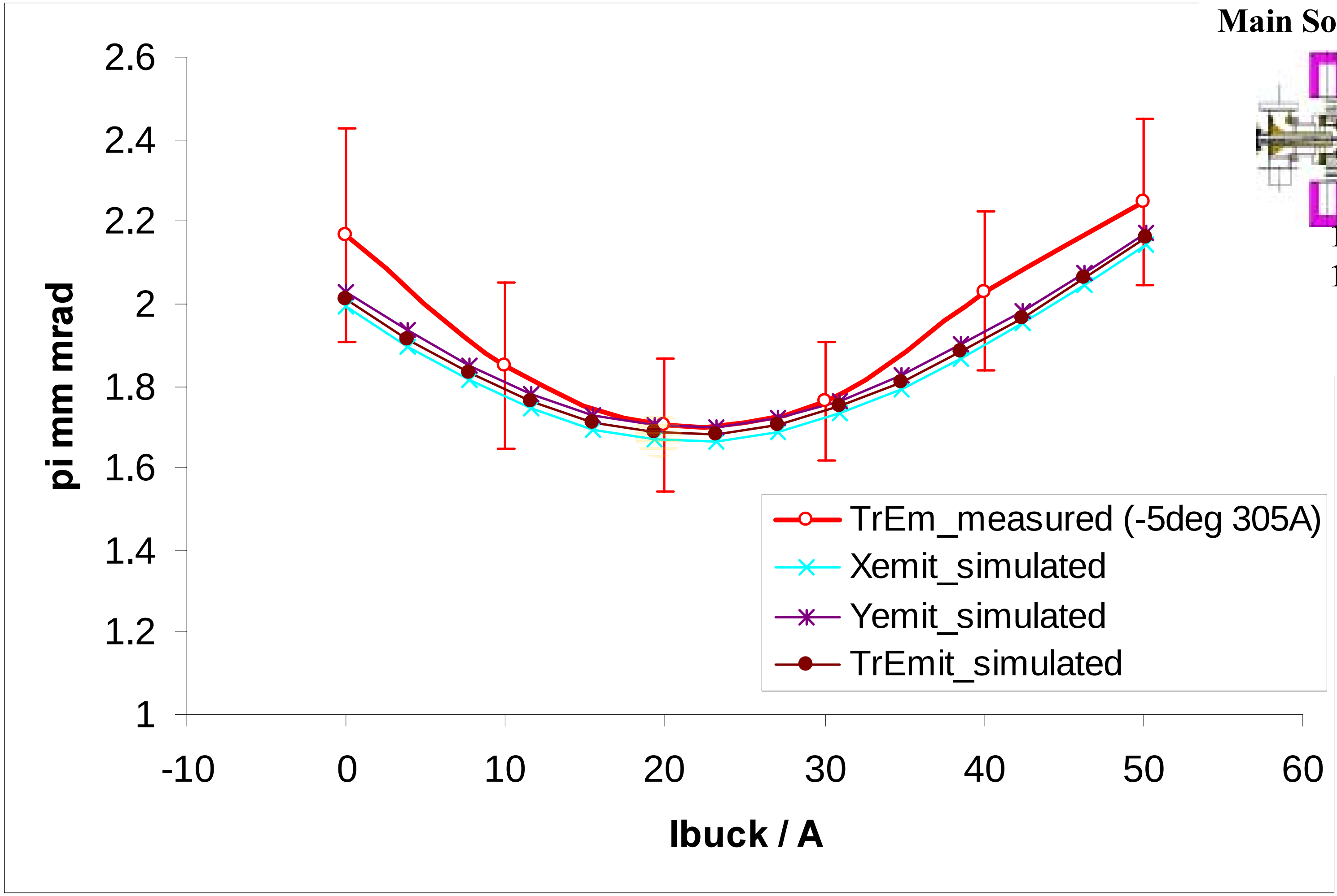
ε(RF Phase, I_{main})

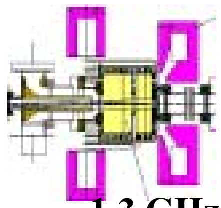
Measured Transverse Emittance vs Bucking Solenoid



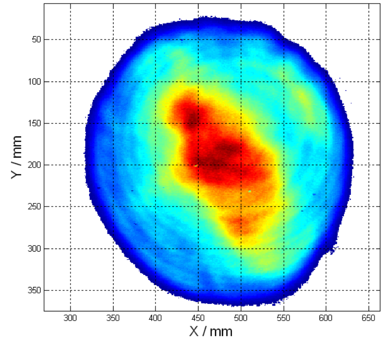
Start-up requirement of TTF2 is clearly fulfilled !

Simulation of Emittance as a Function of Bucking Solenoid





Virtual Cathode



$\sigma_x = 0.55 \pm 0.02$ mm

$\sigma_y = 0.61 \pm 0.02$ mm

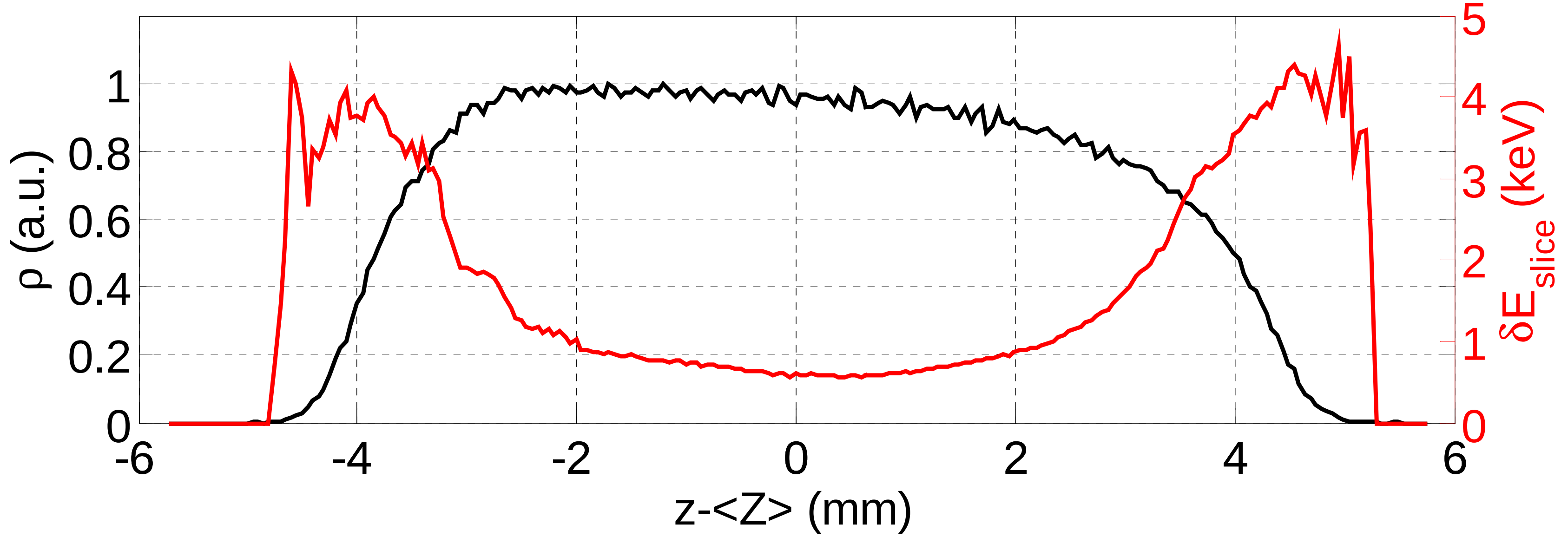
Simulation Parameters (ASTRA):

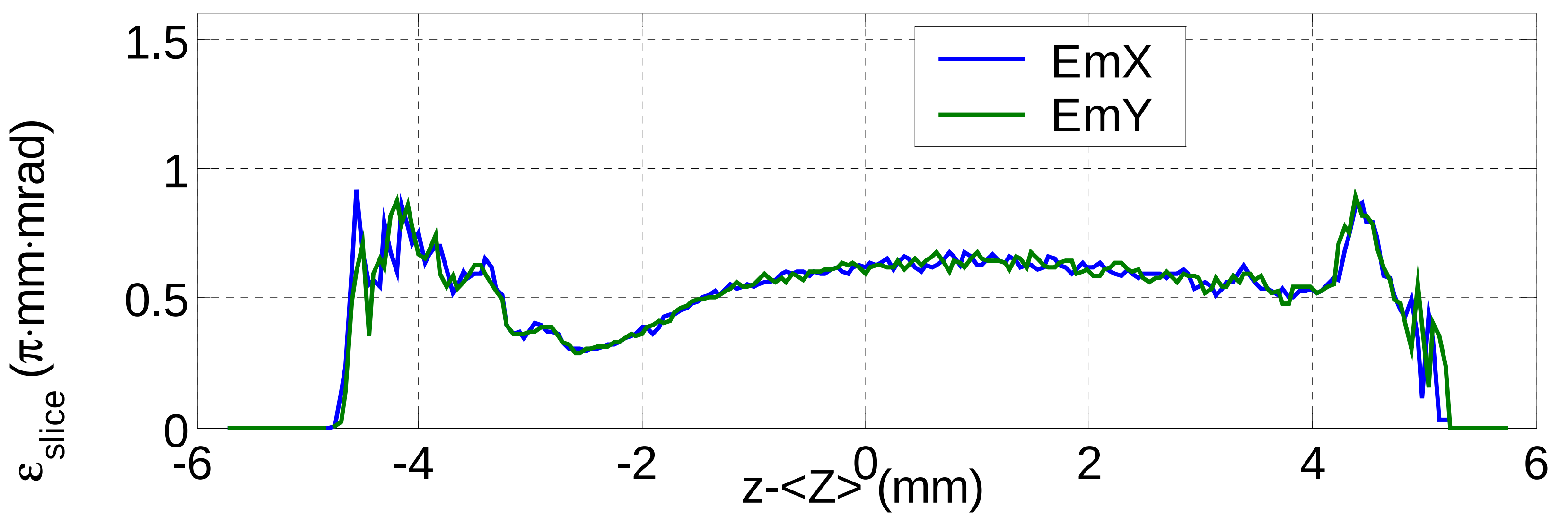
Laser
Long.:Flat-top=22.4/4.3ps
Transv.Homog.XYrms=0.575mm
Therm.Em. Ek=0.55eV

RF
E0=42MV/m
Phase=-1.74deg

Solenoid
Bz(z=0.275m)=-0.174T

Simulated Slice Parameters





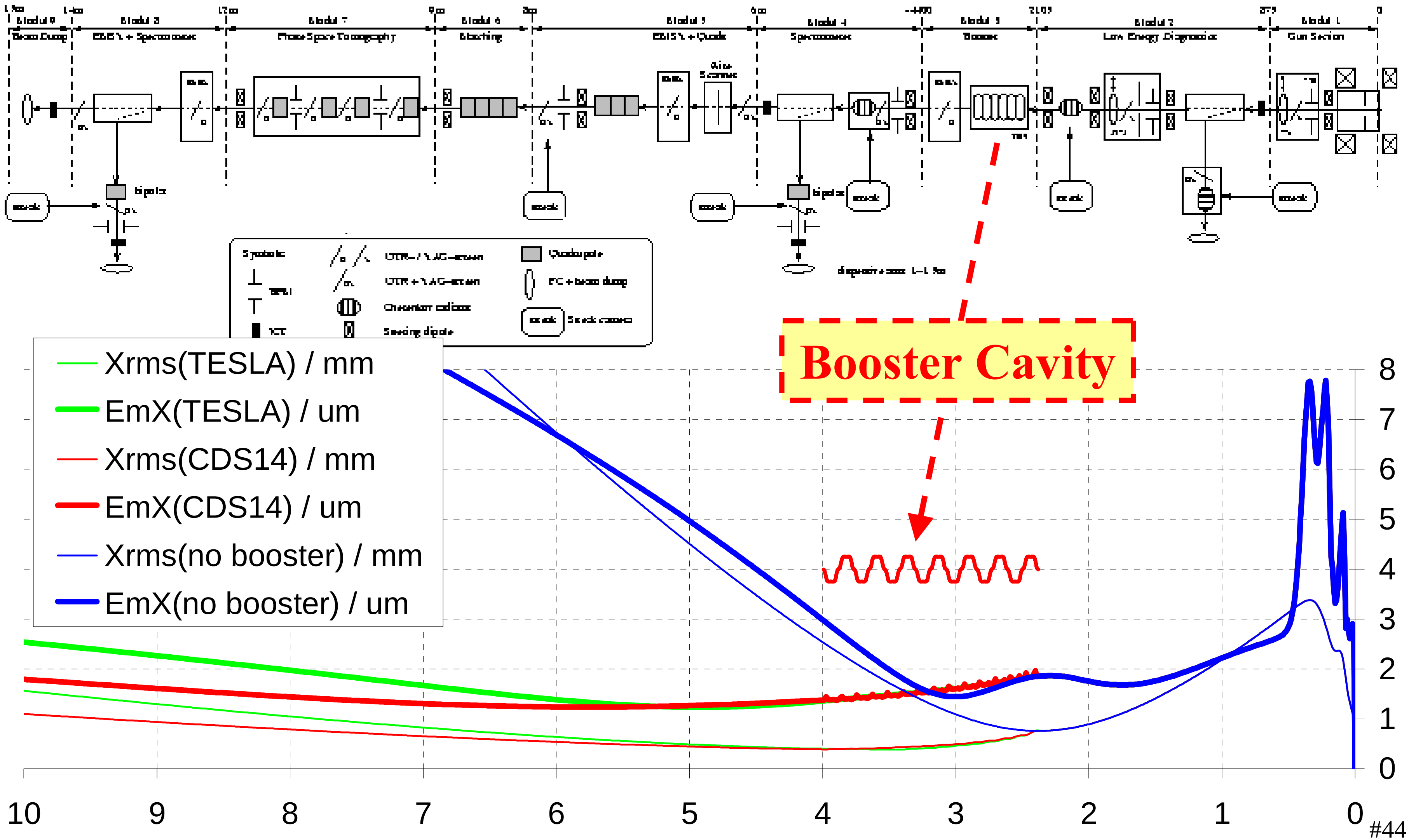
Outlook PITZ 2

study **emittance conservation principle**

booster cavity (TESLA,
CDS - Cut Disc Structure)

further improvement of beam quality

work on laser, cavities, photo cathodes,
developments on simulation tools



Conclusions

Photo Injector Test Facility at DESY Zeuthen (PITZ):

- High duty cycle and high average power operation has been demonstrated
- Electron beam properties have been measured extensively:
    - charge production and transport
    - longitudinal momentum and bunch length
    - transverse beam emittance has been measured for a wide range of parameters;

minimum beam emittance @1nC

$$\varepsilon_y \approx 1.5\pi \text{ mm mrad}$$

$$\sqrt{\varepsilon_x \varepsilon_y} \approx 1.7\pi \text{ mm mrad}$$

have been reached with:

longitudinal laser shape:

'flat top', FWHM ≈ 21 ps, rise/fall time " 7 ps

transverse laser profile:

'homogeneous', σx,y ≈ 0.55 - 0.6 mm

solenoid current:

Imain ≈ 305 A, Ibuck ≈ 20-25 A ! Bz = 0 at cathode

RF parameters:

phase: Φ ≈ Φ0 - 5° , gradient at cathode: ~ 42 MV/m

- Photocathode laser properties are key issues of the succesful photoinjector operation
- PITZ1 gun has been installed at TTF2 in Hamburg in Nov.03
- PITZ2 – large extension of research program

People

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Computer center